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Evaluation of Reflexive Valve Logic for a Shipboard Firemain

ARTHUR DURKIN
FREDERICK W. WILLIAMS

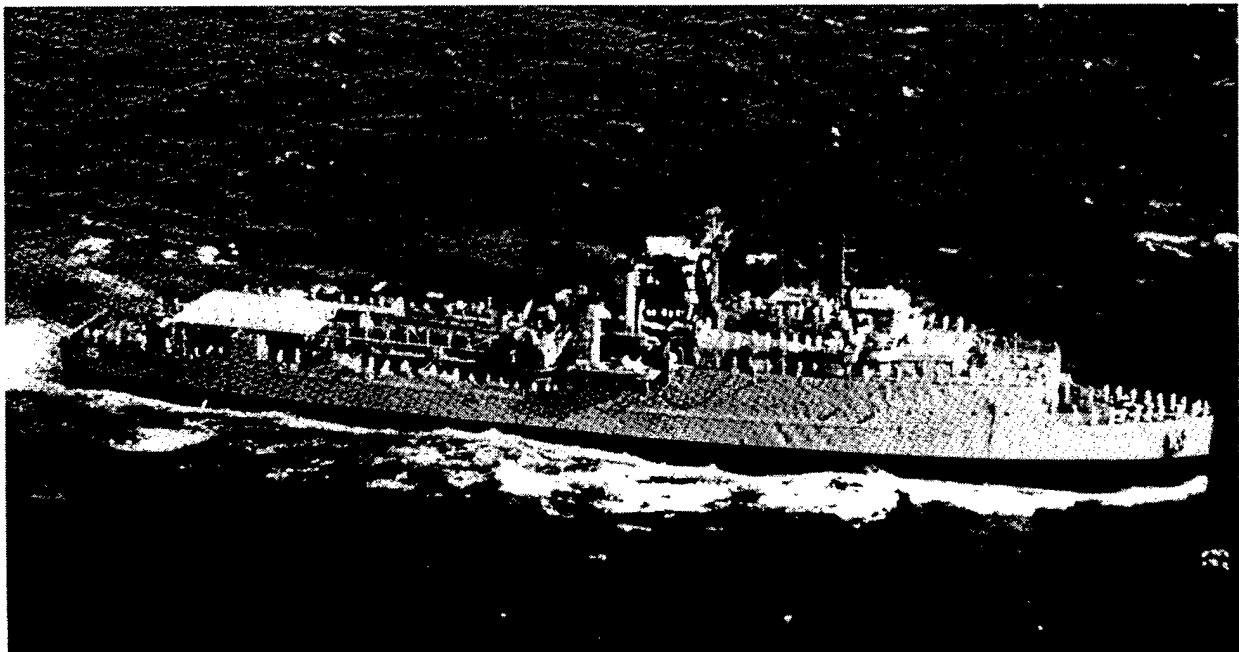
*Navy Technology Center for Safety and Survivability
Chemistry Division*

TOM LESTINA
MELISSA BRADLEY
RYAN DOWNS
ERIC RUNNERSTROM

*MPR Associates
Alexandria, VA*

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13. ABSTRACT (Maximum 200 words) The evaluation of valve logic, which automatically detects, locates and isolates damage to a shipboard firemain is discussed. Based on a review of commercial leak detection technology and shipboard firemain damage response requirements, low pressure, hydraulic resistance, flow inventory and rupture signal detection logic methods are investigated. For low pressure and hydraulic resistance logic methods, setpoints and closure sequences are described and tested using a benchtop model of an offset loop firemain. For flow inventory logic, commercial pipeline leak detection technology is evaluated along with results from a preliminary shipboard firemain demonstration. Rupture signal detection methods are discussed along with potential applications for shipboard fluid systems. Application of logic based on hydraulic resistance is recommended for Navy firemain. The recommended method can detect, locate and isolate the rupture without isolating intact sections and without the need for communication following damage.				
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Evaluation of Reflexive Valve Logic For a Shipboard Firemain

1.0 Summary

The objective of the Damage Control Automation for Reduced Manning (DC-ARM) reflexive fluid system research is to develop and demonstrate the design of fluid systems which respond reflexively to shipboard damage. A reflexive fluid system responds automatically to restore system service following rupture damage without the need for manned response or information from a higher level control system. This is not to say a supervisory control cannot override the systems decisions. Functioning after a weapon hit is a key objective for reflexive fluid systems. Eliminating the need for communications among system components eliminates a critical weakness in survivability. This directs the research to develop a component logic that will function to isolate damage given only information that is available from sensors installed on the component.

This report evaluates different types of reflexive smart valve¹ logic for a shipboard firemain system. The function of reflexive valve logic is to locate piping/valve damage based on data available in the immediate vicinity of the valve. If the data indicates that the valve is adjacent to damage, the valve closes to isolate damage. This report consists of reviewing commercial leak detection technology, developing suitable baseline logic methods and comparing the logic methods using tests performed on a benchtop model and in a ship firemain. The purpose of the evaluation is to identify the most suitable logic to pursue for further development. Enhancement of each baseline logic method is possible to improve performance and reliability; however, the scope of this evaluation is sufficient to identify the core logic to be used in reflexive firemain valves. Baseline methods are developed for low pressure, hydraulic resistance, flow inventory and rupture signal detection logic.

Low Pressure Logic

The reflexive smart valve closes when the local pressure decreases below a low setpoint. Each valve has one of three time delays which is used to sequence the firemain isolation. The valve re-opens when local pressure on both sides returns to normal. Benchtop model tests show that the low pressure logic reliably isolates a rupture even though the number of valve operations may be substantially greater than the minimum required to isolate the rupture. The logic can be readily implemented with different valve, actuator, microprocessor and sensor options. Low pressure logic cannot characterize rupture conditions completely and therefore cannot distinguish a rupture from other hydraulic transients where the piping remains intact. As a result, intact sections of the firemain may be isolated after a rupture and after a pump trip (such as following temporary electrical power failure). While low pressure logic is simple and reliable, it is not

¹ A reflexive smart valve contains onboard sensing, calculation and communication capabilities. A smart valve can operate automatically based on the conditions evaluated.

recommended as the core logic for a reflexive firemain system. Instead, use of low pressure logic as part of hydraulic resistance logic is recommended for a reflexive firemain.

Hydraulic Resistance Logic

The reflexive smart valve detects a rupture when the local pressure decreases below its setpoint and flow rate increases above its setpoint. The combination of setpoints corresponds to the rupture hydraulic resistance². The pressure and flow setpoints may correspond with relative changes in hydraulic resistance (such as for loop isolation valves) or with an absolute minimum acceptable hydraulic resistance (such as for service branch isolation). Once a rupture is detected, a valve closure sequence is initiated. A valve closure sequence has been developed where smart valves nearest the rupture close first. The closure sequence is based on pre-damage operating status of the fire pumps; communication following damage is not needed. If the pressure restores to normal, the closure sequence is terminated. Using the closure sequence, the hydraulic resistance logic can isolate a rupture without isolating intact sections of pipe. The principle limitation of hydraulic resistance logic is the malfunction of pre-damage communication. If pump or valve status information is incorrect before damage occurs, the rupture will be isolated but some intact pipe sections may be isolated also. Hydraulic resistance logic is recommended for implementation as the core logic for the reflexive firemain valves.

Flow Inventory Logic

The reflexive smart valve calculates a flow balance for adjacent pipe segments. Based on local flow measurements, flow measurements from adjacent smart valves, and the status of normal demands, flow imbalances indicate a rupture between the measurement stations. Flow inventory logic is a standard method used by commercial leak detection systems to identify leaks in pipelines greater than 3 gallons/hour. However, no failures at the measurement stations can be tolerated, communication cannot be disrupted, a relatively large number of measurement stations are needed for a flow balance calculation, and high flow measurement accuracy needs to be maintained for successful operation. Methods to compensate for equipment or communication failures (which are expected following fluid system damage scenarios) have not been developed and are expected to be complex. Consequently, flow inventory logic is not recommended as the core logic for a reflexive firemain valve. However, use of flow inventory logic may be considered to enhance the performance of hydraulic resistance logic for selected applications where accurate detection of small leaks is needed such as in fuel or chilled water systems.

Rupture Signal Detection Logic

The reflexive smart valve measures and distinguishes acoustic or vibration signals for intact and damaged piping. Acoustic leak detection is a common commercial method applied to underground piping systems. However, commercial technology would have to be modified for shipboard firemain systems. In particular, limited data is available to distinguish between

² Hydraulic resistance, as used in this report, is defined as the downstream pressure divided by the square of the flow rate.

hydraulic transients for intact piping (such as starting system services or water hammer) and rupture conditions. The Automated Systems Reconfiguration (ASR) program performed by the Naval Surface Warfare Center (NSWC) at Dahlgren and Carderock is currently measuring high speed pressure and pipe vibration data for various hydraulic transients including a warhead detonation that ruptures firemain piping. Evaluation of the ASR data is needed to determine if rupture signal detection is feasible for shipboard firemain. If commercial sensors can distinguish between rupture and intact transient conditions, substantial technology development would be needed to develop the hardware and software suitable for smart valve implementation. Therefore, development of rupture signal detection logic is not recommended for the core logic for a reflexive firemain valve. However, use of rupture signal detection logic may be considered to enhance the performance of hydraulic resistance logic.

Table 1
Summary of Evaluation of Reflexive Firemain Valve Logic

Logic Method	Attributes		
	Rupture Isolation Capability	Tolerant of Failures	Use of Commercial Technology
Low Pressure	<i>Fair</i> May isolate intact piping sections and require a large number of valve operations	<i>Fair</i> Tolerates multiple valve failures. Isolates intact pipe sections following pump trip.	<i>Excellent</i> Uses existing commercial valve and control technology with minimal modification
Hydraulic Resistance	<i>Good</i> Detects and locates ruptures without isolating intact sections.	<i>Good</i> Tolerates multiple valve and pump failures. May isolate intact sections if pre-hit communication fails.	<i>Good</i> Modifies existing valve designs and uses existing sensor and control technology.
Flow Inventory	<i>Excellent</i> Uses a first principles method.	<i>Poor</i> Does not detect a rupture after loss of communication or a valve.	<i>Fair</i> Requires substantial modification of existing commercial leak detection technology.
Rupture Signal Detection	<i>Unknown</i> Insufficient data is available for an assessment.	<i>Unknown</i> Insufficient data is available for an assessment.	<i>Fair</i> Modifies existing commercial acoustic and/or vibration monitoring technology.

Using hydraulic resistance logic, a reflexive firemain can be implemented after the piping design has been completed. The following approach is recommended:

1. Calculate flow rates for ruptures of various pipe sizes in the main loop and branch piping. Identify the flow rates for firemain services and head flow characteristics of the fire pumps.
2. Identify the minimum rupture size to be detected.
3. Identify reflexive smart valve locations and type of hydraulic resistance logic (absolute or relative).

4. Determine reflexive smart valve pressure and flow setpoints.
5. Identify reflexive smart valve closure sequencing and time delays.
6. Identify reflexive smart valve and actuator designs.
7. Implement reflexive smart pump logic.

Implementation of this approach is currently underway on the ex-USS SHADWELL. Development of a concept reflexive valve with embedded microprocessor, inlet and outlet pressure sensors, and transceiver (for network communication) is in progress. Testing of the concept valve on the ex-USS SHADWELL is planned. Reflexive smart pump logic will be implemented once the concept reflexive valve has been tested.

Application of the results of this study to shipboard fluid systems other than the firemain is planned. Conceptual evaluations of a water mist fire suppression system, chilled water system and fuel service system are planned. The approach consists of the following steps:

1. Select a baseline architecture based on current shipboard design practices.
2. Identify the operating requirements for the fluid system (including minimum detectable leak size, required time to restore system operation, number of operating pumps, and vital system demands)
3. Select candidate reflexive valve logic methods based on the operating requirements and the results of this evaluation. For fire suppression system, the candidate logic methods will probably be the same as for the firemain. For fuel service system, additional monitoring methods such as boundary monitoring will be considered.
4. Evaluate candidate logic methods using the same evaluation criteria described in this report. Testing is not planned for this evaluation; instead, the results from this report will provide the basis to identify the most suitable combination of logic methods to meet the operating requirements for these systems.

2.0 Introduction

2.1 Background

The overall objectives of the Shipboard Damage Control Automation for Reduced Manning project (DC-ARM) are to:

- significantly reduce the manning required for damage control,
- significantly reduce the time to execute effective damage control actions and
- provide a high degree of survivability in a manner which will be affordable for installation in Navy ships.

To meet these objectives, development of fluid system technology which can automatically respond to fluid system damage is underway. A reflexive fluid system is one which isolates damaged portions of the system and restores intact sections to service without manned

intervention. System survivability is maximized by automatically isolating damaged portions using only information available at the valve. The use of global information such as pre-damage information from a supervisory control system may enhance system reliability and response time but is not considered necessary for adequate system operation. To the extent possible, commercial components are used in the development of smart valves, pumps and instruments. This reduces the development cost as well as other life cycle costs.

A schematic conceptual configuration of a reflexive firemain is shown in Figure 1.

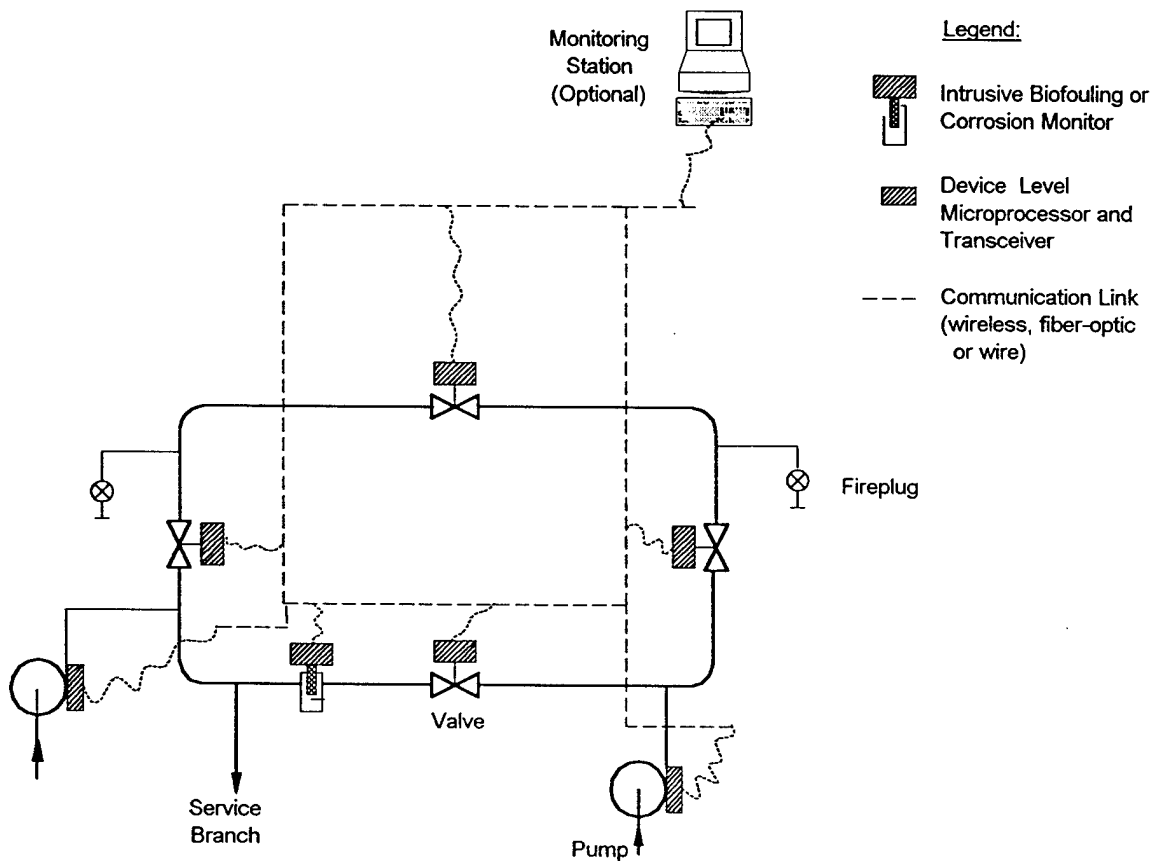


Figure 1. Conceptual Arrangement of Reflexive Firemain

The primary functions of the smart valves are to align flow to operating services and to isolate damaged portions of the firemain, when necessary. The primary function of the smart pumps is to provide sufficient flow to operating services. Additional sensors may be provided to monitor the condition of the firemain for biofouling buildup or material degradation due to corrosion. While communication between components is provided, system level logic is not needed to integrate local sensor data and control firemain valves and pumps. The system monitoring station is needed only for interface with the human or automated supervisor. The system monitoring station would be used to align the firemain for normal operations or maintenance; it is not needed to isolate damage.

The initial evaluation of firemain architectures and supporting reflexive technology has been completed [1]. The evaluation of architectures compared offset loop, dual main and zonal firemain designs. The results of the evaluation indicated that the implementation of a particular architecture involves a trade-off between number of pumps and number of smart valves. It was concluded that the selection of the architecture should be subject to the ship design requirements, and DC-ARM reflexive technology should be developed to apply to any architecture. The work described in this report builds on previous work and investigates specific methods to develop a reflexive smart valve to isolate firemain damage.

The reflexive smart valve development has focussed on implementing advanced sensing technology, communication methods and segregation methods with existing commercial valve and actuator designs. A technology study [1] has shown that commercial technology is available for development of reflexive smart valve components. Some of the technology for automated firemain rupture isolation has been demonstrated. For example, miniature, inexpensive pressure sensors are available from numerous commercial suppliers and testing has shown that differential pressure measurements across firemain valves can be used to measure flow rate [2-5]. In addition, several device-level communication technologies such as LonWorks, Modbus, Profibus, DeviceNet, SDS and Ethernet/TCPIP are available to address the data transmission requirements for a reflexive firemain. LonWorks network protocol for communication between firemain components and for interface with the supervisory control system is currently being demonstrated on the ex-USS SHADWELL [6].

Current US Navy guidance in NSTM 555 [7] specifies that firemain valves should be closed and pumps should be started to restore system pressure following a rupture. Guidance to locate a rupture from a central watchstanding station (when no information is available to help locate a rupture) consists of segregating the firemain into segments (one segment for each pump that can be operated) and starting pumps in isolated segments. The pumps in segments where pressure is restored should remain operating. For pipe segments where pressure is not restored, valves furthest from the pump should be closed first and the pressure should be checked to determine if pressure is restored. This last step should be repeated until pressure is regained. The rupture is located downstream of the last valve closed.

There are several concerns with current Navy doctrine:

- Pressure instrumentation is not installed between all isolation valves. Local pressure indication at each fire pump and one remote indication of firemain pressure for each Zebra segregation in central control is typical. As a result, the watchstander does not readily know the pressure of many firemain segments.
- Intact sections of piping may be isolated.
- A large number of valve closures is needed.
- Depending on the number of isolation valves, substantial effort from the watchstander (with extensive communication with personnel in other spaces) is required to evaluate the pressures and operate the valves.

DC-ARM baseline demonstration testing on the ex-USS SHADWELL has shown that restoring the firemain from a central watchstanding station isolates intact sections and the associated fire plugs [8]. The deficiencies observed are attributed, in part, to the incomplete information available to watchstanders needed to locate ruptures. In particular, pressure instrumentation alone is insufficient to locate a rupture, and systematic valve closures only partially restore the firemain without pinpointing the rupture. The results of the DC-ARM baseline testing indicate that improvements in firemain sensors and doctrine are needed to ensure that a ruptured firemain can be restored.

An initial demonstration of automated firemain rupture detection and isolation logic (developed by NSWC Carderock for the Firemain Reconfiguration Management System) was performed on the ex-USS SHADWELL during the 1998 DC-ARM baseline demonstrations, [8]. The logic used for the demonstration was based on flow balance evaluation between two valves. A rupture between the valves was detected when the flow imbalance increased above a threshold. Once a rupture was detected, the valves closed. Application of this approach is currently being tested for a firemain installed at Aberdeen Proving Grounds as part of the Automated Systems Reconfiguration (ASR) program.

A comparison of different segregation logic methods for shipboard firemain is needed to identify design trade-offs and risks associated with continued technology development. Previous studies sponsored by the US Navy and studies of commercial pipeline leak detection methods do not completely assess logic options which could be applied to shipboard firemain. In particular, full use of information in the immediate vicinity of the smart valve (such that no communication between valves is needed after the damage event) has not been addressed in other work performed to date. An investigation of rupture detection and isolation methods which do not require device communication (or reduce dependence upon device communication) and which are tolerant of multiple component failures is needed.

2.2 Purpose and Scope

This report describes the results of the evaluation and development (where necessary) of segregation logic options for reflexive isolation of a shipboard firemain. The purposes are to identify survivable, reliable and low-cost options for the reflexive isolation of fluid system damage, and to develop an approach that meets DC-ARM objectives. The work consists of a review of commercial leak detection technology and industrial practices to locate damaged sections of piping, classification of the logic methods identified, development of enhancements to achieve DC-ARM objectives and comparison of the methods using a benchtop model of a firemain. The four classifications are based on the discussion in [1]:

- Low Pressure. The valve closes when the local pressure decreases below a low pressure setpoint.
- Hydraulic Resistance. The valve closes when the hydraulic resistance downstream of the valve decreases below a setpoint.

- Flow Inventory. The valve closes when the flow in an adjacent pipe segment is imbalanced.
- Rupture Signal Detection. The valve closes when the fluid-borne acoustic signature or pipe vibration signature matches rupture characteristics.

Based on the results of the comparison, a suitable method for implementation of reflexive system technology for a shipboard firemain is identified.

A discussion of various reflexive pump logic methods is not included in this report. Instead, smart valve logic is evaluated based on different applications of existing fire pump operation. In particular, smart valve logic should be able to accommodate the following fire pump operation modes:

- Manual Pump Start Prior to Rupture. Based on pre-hit information or battle orders, manual start of redundant pumps may be performed by the central watchstander.
- Automatic Pump Start on Low Pressure. Designated pumps may automatically start when the local pressure decreases below its setpoint.

Development of specific smart pump logic will be performed as follow-on work after smart valve logic is developed.

3.0 Approach

This section discusses the functional requirements of a reflexive firemain, identifies the associated evaluation criteria for the reflexive valve logic, describes the scope of the survey of commercial logic methods and describes the benchtop model used to test logic methods.

3.1 Reflexive Functional Requirements

The overall goal of developing a reflexive fluid system is to demonstrate the operation of the components and logic sequences which respond automatically to fluid system damage without the need for communication among components after damage. Specific functional objectives include the following:

1. Rupture Isolation. The reflexive system should be able to isolate a rupture and restore system services to intact portions of the firemain. Detection and isolation of smaller leaks are not considered critical to reflexive system operation because the flow rates to firemain services remain adequate and firemain pressures are not reduced for small leaks which are not caused by the rupture of piping [9]. The rupture isolation should be accomplished without increasing the safety hazard to ship personnel who may be using the firemain for firefighting. As a result, trial and error cycling of valves to locate a rupture is not acceptable since firemain pressure may be lost to firefighters during a valve cycle.
2. No Manned Intervention. The system should perform damage isolation and service restoration actions without manned intervention.
3. No Communication Following Damage. The system should perform damage isolation and service restoration actions without communication (after damage) with the supervisory control system or between smart components in the system. If communication is available, it may be used to enhance system performance beyond the minimum requirements.
4. Tolerant of Multiple Failures and Degradation. The system should be able to operate successfully with failures of more than one valve or pump in addition to other degradation expected in shipboard firemain. For example, buildup of fouling product (corrosion and biological) is expected and the system should be able to operate with buildup of such product.
5. Simple and Reliable Design. The system should isolate damage and restore services with a minimum number of components with a design based on proven technology that is straightforward to implement. In general, simple designs contain fewer components and minimal processing requirements for the component level controller.
6. Low Cost. The system must have a low life cycle cost. The maintenance effort must be kept to a minimum to meet manning objectives for future ships. Reducing the number of active components in the system will help minimize life cycle cost.

3.2 Evaluation Criteria

The method of evaluation consists of establishing "baseline" logic suitable for implementation on a device-level microprocessor. The baseline logic is assessed using the following criteria:

Capability to Isolate a Rupture

This criterion addresses functional requirements 1 and 2 listed above. The capability to isolate a rupture is evaluated using an offset loop design and rupture location as shown in Figure 2. Attributes evaluated include number of valve operations and number of intact pipe segments isolated. The evaluation expands upon the screening evaluation in [1] by assessing the isolation sequence for each baseline logic method. Loss or malfunction of a pump or valve is considered separately and is not included in this part of the evaluation.

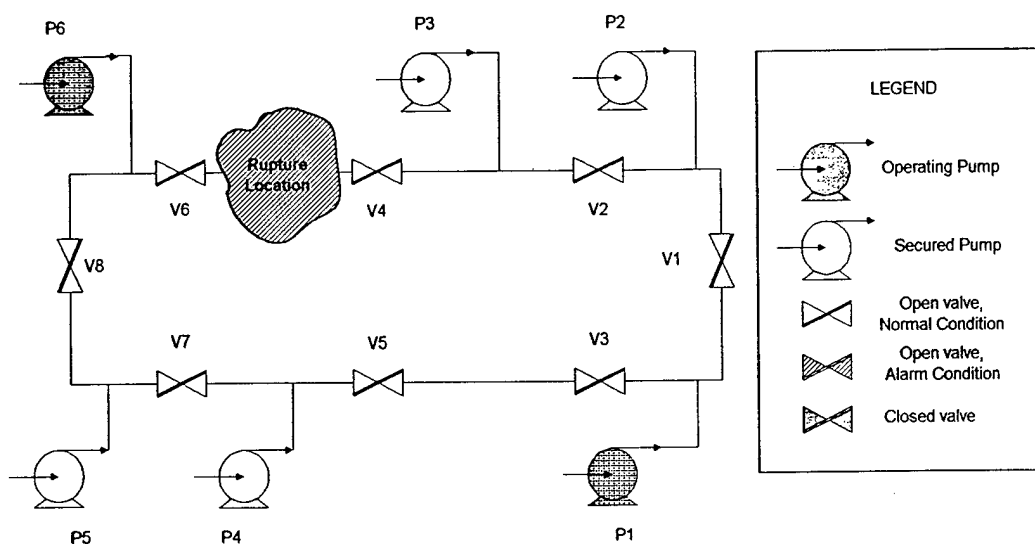


Figure 2. Typical Loop Firemain Configuration and Rupture Location

Limitations and Failure Modes

This criterion addresses functional requirements 3 and 4. Based on the results of rupture isolation sequences tested, limitations of each logic method are identified. A comprehensive failure modes and effects evaluation is not performed; instead, limiting characteristics based on the fundamentals of the methods are assessed. Methods to correct or compensate for these limitations are discussed.

Application of Commercial Technology

This criterion addresses functional requirements 5 and 6. In general, the simplicity, reliability and cost requirements can be met if commercial hardware and software can be adapted and used with minimal development effort. Application of commercial technology is demonstrated using the benchtop model or other demonstration platform (such as the ex-USS SHADWELL or ASR test facility in Aberdeen). Attributes evaluated include the size of the

software program to implement the logic, the required accuracy of the setpoints, and availability of commercial suppliers for the technology used.

3.3 Survey of Commercial Logic Methods

A survey of commercial technology which detects and locates leaks in pipelines has been performed. The survey expands upon the valve and sensor survey performed in [1] (which addressed hardware issues) to identify candidate integrated hardware and software technology which may be adapted for reflexive fluid system development. The results from these surveys are used as the basis for evaluation of the capability of applying commercial technology for reflexive valve development.

The survey has focussed on development of automated pipeline leak technology to address the EPA requirements and performance standards for leak detection of hazardous liquids in underground storage tank and piping systems [9]. Owners and operators of pressurized underground piping must perform hourly on-line testing and either a monthly or annual line tightness test:

- **Hourly Test.** Leaks greater than 3 gallons/hour shall be detected within one hour. The system shall have an automatic shutoff device, an automatic flow restrictor, or continuous alarm system for leaks greater than 3 gallons per hour.
- **Monthly Test.** A monthly test shall be performed to identify leaks greater than 0.2 gallons/hour.
- **Annual Test.** In lieu of the monthly test, an annual test may be performed to identify leaks greater than 0.1 gallons/hour.

A variety of commercial technologies have been under development for more than ten years to address these requirements. In general, commercial pipeline leak detection systems are for small leaks in petroleum pipelines, and therefore the results of this survey are applicable to fuel service systems which will be evaluated in future work.

3.4 Benchtop Firemain

A model of an offset loop firemain has been assembled to test rupture logic methods and debug device-level software. The model shown in Figure 3 consists of six pumps, twelve valves, a 10 gallon basin of water and two interconnected headers of tubing with elevations offset by one foot. Eight solenoid-operated valves are installed in the main loop, and four manual valves are installed in branch piping to control flow for the rupture and vital load simulation. The centrifugal pumps which are rated at a nominal 6 gpm draw suction from the water basin and supply waters to the headeers through six dedicated risers. A rupture is simulated by directing water to the basin through two manually operated quarter-turn valves. A description of key components for the model is provided in Table 2.

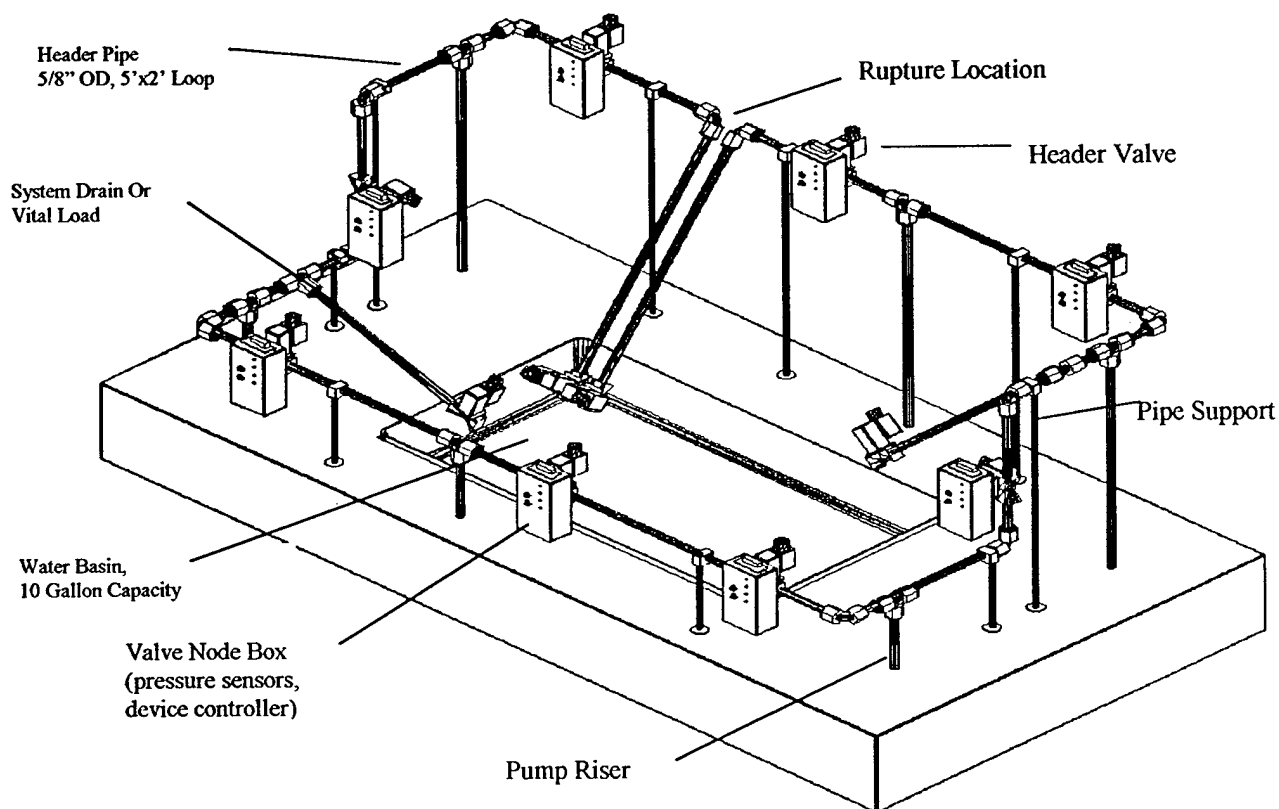


Figure 3. Benchtop Model of an Offset Loop Firemain

Table 2

Description of Key Components for the Firemain Benchtop Model

Component	Description
Pump	1/12 hp, 115 Vac centrifugal pump/motor combination, 62 ft shutoff head, 360 gallons per hour capacity, 3/4 inch hose connection,
Header Valve	1/2 inch solenoid valve, 115 Vac, 230 psi rating
Pipe	5/8 inch clear acrylic tubing, 1/16 inch thick
Pressure Sensor	0-700 kPa, 0.2-4.7 volt output, Motorola MPX5700 Series piezoresistive transducer
Device Microprocessor	Echelon Generic Control Module, Model TP/FT-10F (55020-10) which includes Neuron 3150 chip, flash memory socket, and communication transceiver

Each pump and eight valves are equipped with device-level controllers. Each controller can communicate with the other controllers using LonWorks network communication protocol. A personal computer is used to develop and download logic onto flash memory chips located in each controller. Each valve controller contains two pressure sensors with taps located at the valve inlet and outlet. The pressure sensor and valve configuration models a smart valve arrangement.

The hydraulic characteristics of the benchtop model are substantially different than the characteristics of a shipboard firemain. In particular, the following hydraulic differences were observed:

- Valve Flow Coefficient. Compared to shipboard firemain valves, the solenoid valves used in the benchtop model have a substantially higher pressure loss (a couple psi differential instead of a few inches of water differential for shipboard firemain valves)
- Valve Closing Time. The solenoid valves used in the benchtop model have a lower closure time (less than a second) compared to the 20-30 second closing time for shipboard firemain valves.
- Firemain Pressures. The pressure in the main loop of the benchtop model is approximately 17-20 psig for most of the test runs. The pressure of shipboard firemain is typically 120-170 psig.
- Leak-Tightness of System. The benchtop model is a "tight-sealing" system and pressure did not decrease when pumps were stopped unless some leakage path (such as leaking valve or rupture) was provided. Shipboard firemain is rarely "tight-sealing" and pressure is not maintained when pumps are stopped due to a number of possible leak paths (such as leak by of the check valves in the pump discharge or operating service demands).
- Elevation Differences. The elevation difference between the high and low mains in the benchtop model is one foot, whereas the elevation difference between the mains in an offset loop shipboard firemain is typically more than 10 feet to maintain adequate deck separation.
- Trapped Air. Removing all trapped air from the benchtop firemain proved to be difficult prior to a test run. A small amount of trapped air had a significant effect on the flow direction during some of the tests. Trapped air does not have a significant effect on flow direction for shipboard firemain.

These differences did have an effect on the test results from the benchtop model. In particular, low pressure and valve differential pressure setpoints, valve timing sequences, pressure transients and flow direction were affected. However, these differences did not adversely affect the results of concern for valve logic evaluation. In fact, unexpected hydraulic conditions experienced during benchtop model tests helped to evaluate the reliability of the logic methods. Where the results are affected by the modeling differences, the impact is discussed.

Implementation of variations of low pressure and hydraulic resistance logic have been tested with the benchtop model as part of this evaluation. Testing of flow inventory logic was not considered necessary because a demonstration of the flow inventory logic developed as part of the Firemain Reconfiguration Management System (FRMS) program was provided during the DC-

ARM baseline demonstration testing in 1998 [8] and continued evaluation is currently underway as part of the ASR program. Testing of rupture signal detection logic is not practical using the benchtop model.

4.0 Results and Discussion

4.1 Commercial Pipeline Leak Detection Technology

A variety of commercial technologies are employed to meet the Environmental Protection Agency (EPA) requirements for pipelines which contain hazardous fluids including mechanical leak detectors, groundwater monitoring, automatic tank gauging, secondary containment with interstitial monitoring and statistical inventory reconciliation. In addition to monitoring hazardous liquids such as petroleum products, monitoring of water distribution systems has been performed to detect and correct leaks. In general, the commercial leak detection technology can be divided into the following classifications:

Mechanical Leak Detection

Mechanical leak detectors are hydraulic valves designed to detect leaks greater than 3 gallons/hour in fuel dispensing systems. A line leak test is performed on the startup of the fuel pump. The valve moves from a flow restricting position to an open position if the fuel nozzle is pressurized (no leak condition). If a leak greater than 3 gallons/hour is present, pressure at the nozzle remains low and the valve remains in the flow restricting position. Such equipment has been available for more than ten years; however, its application is restricted to particular applications such as service station tank and fuel nozzle systems [11,12].

Compensated Volume Balance

This common method of leak detection measures the "volume in" and subtracts the "volume out". Variations of this method have been demonstrated at pipeline installations for more than 10 years [13-17]. Volumetric flow rate, temperature and pressure data are measured at several measurement locations and transmitted to a central computer station via data links as shown in Figure 4. Based on the leak model used by the central computer, the system calculates if a flow imbalance is characteristic of a leak.

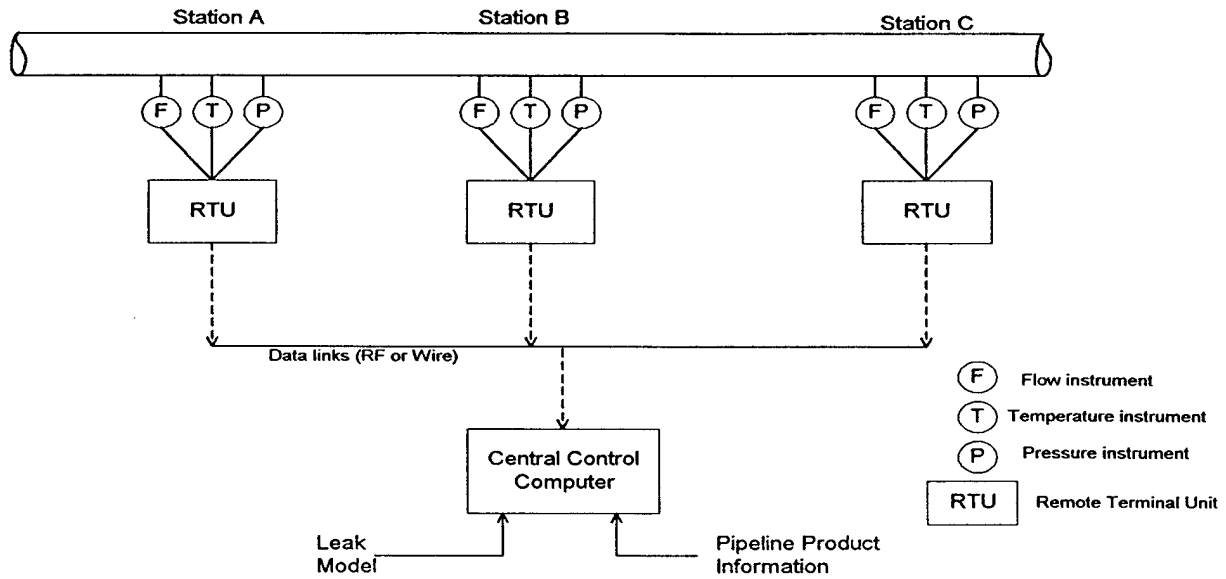


Figure 4. Overview of Typical Pipeline Leak Detection System Using Compensated Volume Balance

While simple in concept, implementation has required careful attention to detail. To illustrate this, consider a model of a simple pipeline segment with a constant flow cross section based on the general one-dimensional form of the continuity, momentum and energy equations as described in [18] based on traditional development [19,20]:

Continuity
$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho V)}{\partial x} = 0 \quad (1)$$

Where ρ = fluid density, lbm/ft³ (kg/m³)
 t = time, s
 V = fluid velocity, ft/s (m/s)
 x = location along pipeline segment, ft (m)

Momentum
$$\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} + \frac{g_c}{\rho} \frac{\partial P}{\partial x} + g \frac{\partial z}{\partial x} + \frac{fV|V|}{2d} = 0 \quad (2)$$

Where P = pipeline pressure, lb/ft² (Pa)
 g_c = units conversion constant = 32.2 lbm-ft/lb-s² (1 kg-m/N-s²)
 g = acceleration due to gravity = 32.2 ft/s² (9.81 m/s²)
 z = pipe elevation, ft (m)
 f = pipe friction factor, dimensionless
 d = pipe inside diameter, ft (m)

$$\text{Energy} \frac{\partial T}{\partial t} + V \frac{\partial T}{\partial x} - \frac{1}{\rho c_p J} \left(\frac{\partial P}{\partial t} + V \frac{\partial P}{\partial x} + \frac{\rho}{2g_c} \frac{f|V|^3}{d} \right) + \frac{4U}{\rho c_p d} (T - T_o) = 0 \quad (3)$$

Where T = fluid temperature, °F (°C)
 c_p = specific heat of fluid, Btu/lbm·°F (J/kg·°C)
 J = units conversion constant = 778 ft·lb/Btu (1 N·m/J)
 U = overall heat transfer coefficient between fluid and ambient surroundings, Btu/s·ft²·°F (W/m²·°C)
 T_o = ambient temperature, °F (°C)

Under steady conditions, leak conditions can be detected using the continuity equation where $\partial \rho / \partial t = \partial (\rho V) / \partial x = 0$ and the equation of state calculates the density as function of temperature and pressure, $\rho(T, P)$. However, conditions are often not steady in a pipeline due to changes in product properties and changes in flow rate due to system startup, demand variations and compressor/pump trips. During non-steady conditions, flow is not balanced and solution of the continuity, momentum and energy equations becomes necessary to detect a leak. As a result, accurate calculation of leaks under non-steady conditions requires more information and becomes more complicated.

The accuracy of the compensated volume balance method depends upon the accuracy of the measurements (particularly the flow measurements), system commissioning and tuning practices, and the type of leak model used for evaluation (steady state or transient). For leak detection systems developed before the EPA requirements, flow instrumentation with overall accuracy within 1% is typical [16,17]. System tuning is typically performed during non-leak conditions to compensate for instrument bias, drift and variations in system pipe roughness [15,18]. If compensation for flow instrument bias and drift is performed, the repeatability, and not overall accuracy, of the instrumentation determines the detection capability. Flow instrument repeatability within 0.05-0.25% has been reported for early systems [13, 16, 17]. The minimum detectable leak size for early demonstration pipeline projects is reported to be 1-3% under steady conditions [15, 17] and 4% under transient conditions [15].

To meet EPA requirements, the minimum detectable leak size must be less than the leak sizes detected in these earlier demonstration projects. The EPA has developed test procedures to evaluate the performance of leak detection systems [21]. In general, the method consists of measuring system data during non-leak conditions and comparing the results under controlled leak conditions. The signal plus noise measured under leak conditions should be distinguished from the noise measured under non-leak conditions for at least 95% of more than 25 test runs. Careful system tuning is necessary to meet EPA requirements.

Pressure Wave Acoustic Leak Detection

Acoustic monitors installed along a pipeline can detect and locate a leak by timing a pressure wave which originates from a leak location [16,22]. The low pressure acoustic wave

disturbance moves away from the leak location at a speed near the sound speed of the fluid in the pipe. Based on the difference in time the wave is detected at neighboring monitors, the distance between the monitors, and the wave speed, the leak location can be determined. The system consists of several acoustic monitors which include a pressure sensor (piezoelectric or piezoresistive), signal processing circuits and a transceiver which sends data to a central computer station for evaluation of leak location. System tuning under non-leak and controlled leak conditions is essential to distinguish between normal fluid noise and a leak signal. Suppliers of acoustic monitors which meet the EPA detection requirements are available commercially.

Boundary Monitoring

Pipeline leaks can be detected by sensing the fluid presence outside the pipe. The EPA considers ground water monitoring, soil vapor monitoring and interstitial monitoring of secondary containment acceptable methods to meet leak detection requirements [23]. Boundary monitoring technology is available from several suppliers. In addition to these standard monitoring technologies, other boundary monitoring technologies have been used. For example, an airborne thermal image survey has been used to detect minor leaks (2-10 m³/day) for a water pipeline [13]. In addition, a hydrocarbon sensing cable has been developed to detect and locate leaks when a polymer coating swells in contact with certain fluids [13]. The swelling changes the resistance measured in the cable which is monitored remotely. The resistance value is used to determine the location of the leak.

It is considered impractical to establish reliable leak or rupture detection for a shipboard firemain based on the discharge and/or buildup of water in a compartment because small amounts of water buildup is common during normal shipboard activities due to condensation, housekeeping and maintenance actions. Furthermore, water buildup is expected following damage or fire conditions.

Pipe Integrity Monitoring

Numerous technologies are available to monitor piping for flaws and degradation in wall thickness. In general, methods are manual and are used for pipe inspections to support maintenance and replacement decisions. It may be possible to adapt some of these technologies to permit automated "pitch-and-catch" between smart valves where a signal is transmitted by one smart valve along the pipe and received by a neighboring smart valve. If the signal is disrupted, pipe damage is indicated. Based on [24], some potential technologies include:

- **Magnetostrictive Guided Wave.** A magnetostrictive system consists of transmitter and receiver units each with coils and magnets which encircle the pipe. Electromagnetic waves are transmitted along the pipe, defects in the pipe disrupts the signal, and the receiver unit detects and interprets the disrupted signal.
- **Piezoelectric Guided Wave.** A piezoelectric system consists of piezoelectric transducers which produce a periodic vibration along the pipe. The vibration response is disrupted by defects or damage in the pipe.

Development of these technologies for rupture or leak detection of shipboard firemain is considered to be expensive and may not work. As a result, further consideration is not warranted since methods which are based on system hydraulic characteristics are more promising.

4.2 Low Pressure Logic

Low pressure logic consists of closing a valve when the pressure in the pipe decreases less than the set point. To evaluate low pressure logic capabilities and limitations for a firemain system, the following key features are applied to the baseline logic:

1. Pressure Monitored at Smart Valve Inlet and Outlet. Pressure is monitored at the inlet and outlet of each smart valve. Communication via a network is provided for supervisory monitoring but is not needed between valves and pumps.
2. Single Low Pressure Closure Setpoint. Smart valves close when pressure at the inlet and outlet decreases below and remains below the low pressure setpoint throughout the time delay period. The same setpoint is applied for all valves.
3. Sequential Segregation. The firemain is segregated sequentially with the use of time delays when pressure is less than the setpoint. The sequence of valve closures is established with one of three closure priorities for smart valves in the main headers and cross-connects:
 - a. Priority 1 Valves. These valves close with no or very little time delay when pressure is reduced below the low pressure setpoint. The function of Priority 1 valves is to segregate the firemain as soon as possible after fault conditions are identified. The valves are equivalent to ZEBRA valves for current firemain.
 - b. Priority 2 Valves. These valves perform backup function for the Priority 1 valves. These valves close with a time delay greater than for Priority 1 valves. These valves close only if closure of Priority 1 valves has not restored system pressure.
 - c. Priority 3 Valves. These valves close if the closure of Priority 1 and 2 valves does not restore system pressure. The time delay for Priority 3 valves is greater than for Priority 1 and 2 valves.
4. Smart Valves Re-open With High Pressure. When pressure at the inlet and outlet of each valve increases above the setpoint, the valve re-opens. In addition, if the pressure increases before the time delay has expired, the valve does not close and the time delay is reset.

The time delay for a smart valve with low pressure logic is a function of the valve priority, valve closing time and system hydraulic characteristics. The time delay should allow system transient characteristics to stabilize and ensure that higher priority valves have cycled. As an example, the closing time for 4-inch quarter turn butterfly valves with Keystone motor operated actuators (as installed on the SHADWELL firemain) is 20 to 25 seconds. Assuming that hydraulic transients stabilize after a few seconds, time delays can be set at 5 seconds for Priority 1 valves, at 30 seconds for Priority 2 valves and at 55 seconds for Priority 3 valves.

The low pressure logic described above has been tested on the benchtop model. The results from three tests are presented in this report.³ The test alignments can be classified as follows:

- Test 1: Rupture with no system degradation
- Test 2: Rupture with one valve disabled open
- Test 3: Rupture with three valves disabled open

The test alignments are shown in Tables 3, 4 and 5. The results are shown in Figures 5, 6, and 7. The results of the comparison with the evaluation criteria is summarized below:

Capability to Isolate Rupture With Low Pressure Logic

Rupture conditions result in low firemain pressure. Low pressure conditions result in inadequate flow to firemain services and corrective action is needed. Based on these fundamentals and the results of the benchtop tests, low pressure logic can be used to isolate a rupture reliably. However, a large number of valve operations is often required, and sometimes intact pipe sections are isolated. For tests 1, 2 and 3, two to eight valve operations were required, and zero, one or two intact piping sections were isolated⁴. The need for more than two valve closures and isolation of intact pipe sections are inherent features of low pressure logic because low pressure alone is insufficient to locate a rupture. As a result, additional logic is needed to restore operation to intact pipe sections or reduce the number of valve operations. This additional logic could be pump logic which automatically starts a pump when pressure is low or a supervisory algorithm which uses data other than firemain pressure data.

Failure Modes and Limitations with Low Pressure Logic

Low pressure logic can isolate a rupture with multiple valve failures. Low pressure logic can not distinguish between a pump trip (with only one pump operating) and a rupture. As a result, all valves will close following a pump trip if pump operation is not restored. Upset conditions such as temporary loss of electrical power could result in loss of all pumps and all smart valves would close. Additional logic such as a supervisory algorithm is needed to restore the valve line-up after pump operation is restored.

³ A total of nine test runs were performed. Two test runs were performed with a rupture and no system degradation; two test runs were performed with a pump trip; two test runs were performed with a rupture and one valve disabled; and three test runs were performed with a rupture and three valves disabled. The three tests shown represent a cross section of the results for both optimal and non optimal valve sequences. For all rupture test runs, the rupture was isolated. For the pump trip test runs, all valves closed once the pressure was reduced.

⁴ It is noted that for test 3 only two valve operations were needed and no intact sections were isolated. While it is possible to attain this performance with precise low pressure setpoints, the results are not considered representative of a shipboard firemain. With test 3 alignment on a shipboard firemain, more than two valve closures and isolation of intact pipe sections is expected. Hydraulic analyses indicate that the firemain pressure near the rupture is approximately the same as the pressure in segments furthest from the rupture (at similar elevations).

Application of Commercial Technology with Low Pressure Logic

Low pressure logic is considered the simplest method to implement using commercial components. A number of different methods of implementing low pressure logic are available using existing commercial technology. These include use of hydraulic valves which close when pressure is low, use of commercial pressure transducers which communicate actuation signals to neighboring valves, and embedding commercial pressure sensors in existing valve body designs. The software embedded in the microprocessor is simple to develop. It is possible to implement the low pressure logic described using commercial pneumatic or hydraulic components without a microprocessor. For example, a hydraulic valve with a diaphragm actuator could be configured to open when pressure is normal and close when the pressure is less than the setpoint.

Table 3
Input and Initial Conditions for Test 1 Using Low Pressure Logic
on the Benchtop Model

Low Pressure Setpoint:	10 psig
Valve Priorities:	Priority 1: V1 and V8 Priority 2: V4 and V5 Priority 3: V2, V3, V6, and V7
Valve Time Delay:	Priority 1: 1 second Priority 2: 5 seconds Priority 3: 10 seconds
Pump Operation:	Manual
Initial Pump and Valve Alignment:	V1 to V8 open P1, P6 operating
System Degradation	None
Rupture Location:	Between V4 and V6

Table 4
Input and Initial Conditions for Test 2 Using Low Pressure Logic
on the Benchtop Model

Low Pressure Setpoint:	10 psig
Valve Priorities:	Priority 1: V1 and V8 Priority 2: V4 and V5 Priority 3: V2, V3, V6, and V7
Valve Time Delay:	Priority 1: 1 second Priority 2: 5 seconds Priority 3: 10 seconds
Pump Operation:	Manual
Initial Pump and Valve Alignment:	V1 to V8 open P1, P6 operating
System Degradation	V4 disabled open
Rupture Location:	Between V4 and V6

Table 5
Input and Initial Conditions for Test 3 Using Low Pressure Logic
on the Benchtop Model

Low Pressure Setpoint:	10 psig
Valve Priorities:	Priority 1: V1 and V8 Priority 2: V4 and V5 Priority 3: V2, V3, V6, and V7
Valve Time Delay:	Priority 1: 1 second Priority 2: 5 seconds Priority 3: 10 seconds
Pump Operation:	Manual
Initial Pump and Valve Alignment:	V1 to V8 open P3, P6 operating
System Degradation	V1, V4, and V8 disabled open
Rupture Location:	Between V4 and V6

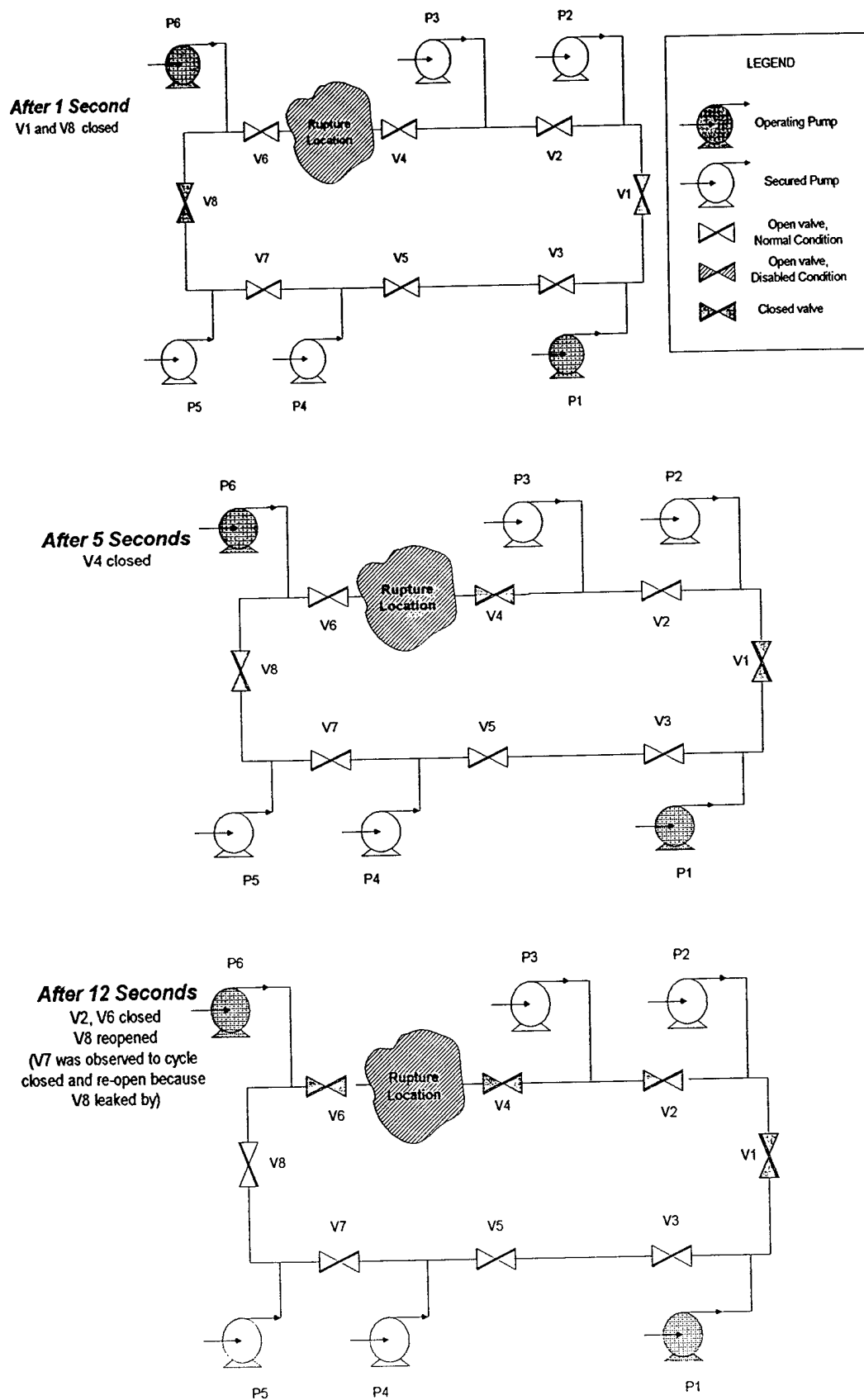


Figure 5. Results of Rupture Isolation Using Low Pressure Logic on the Benchtop Firemain for Test 1

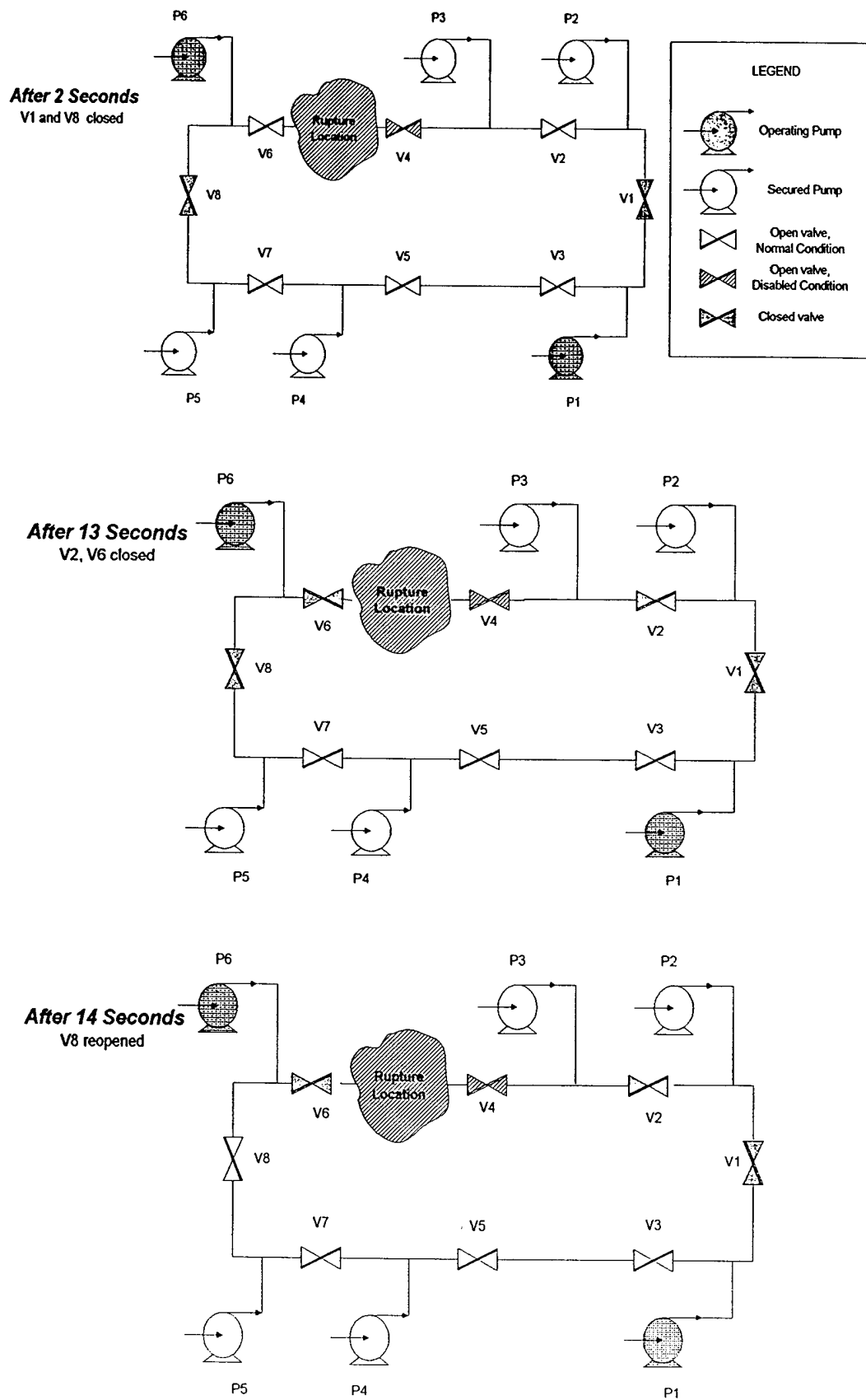


Figure 6. Results of Rupture Isolation Using Low Pressure Logic on the Benchtop Firemain for Test 2

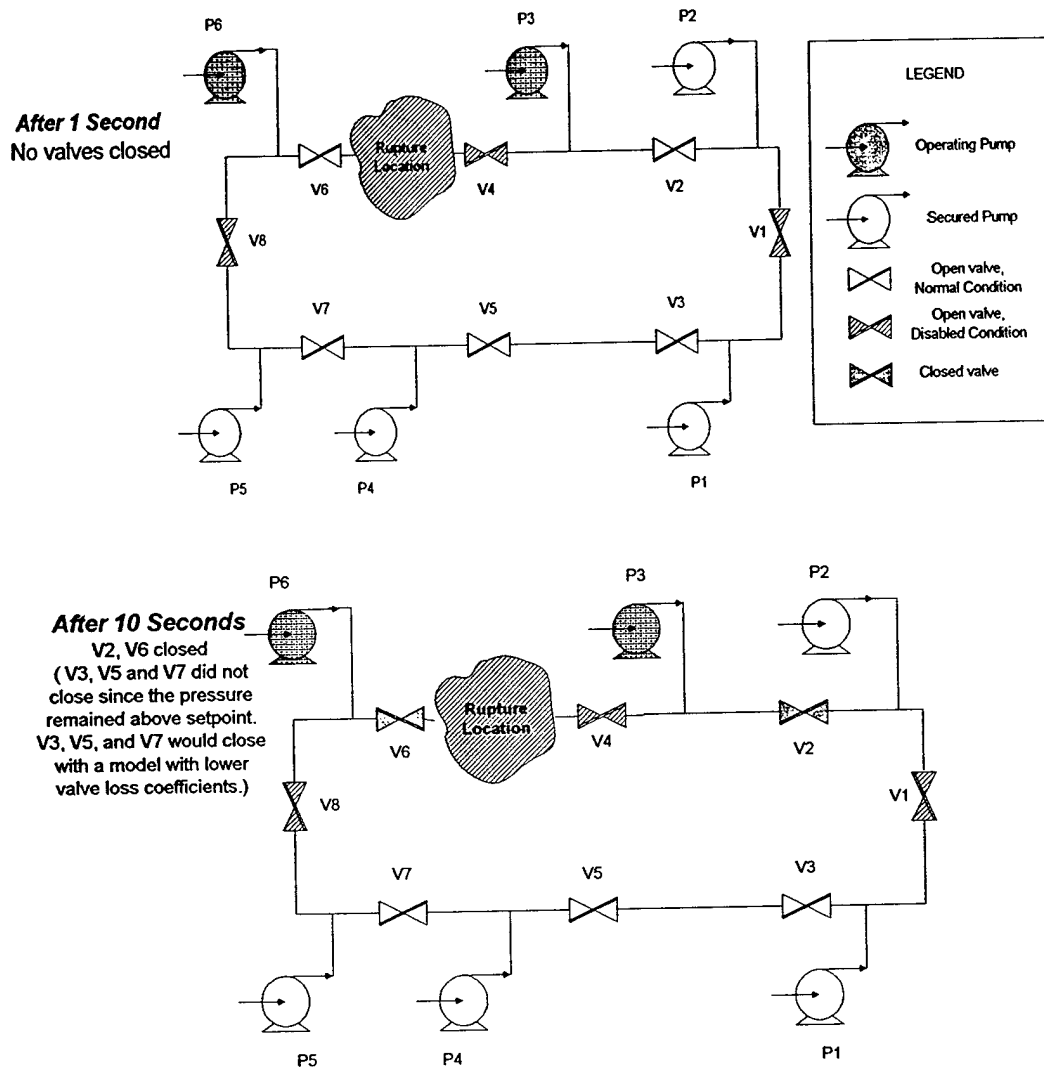


Figure 7. Results of Rupture Isolation Using Low Pressure Logic on the Benchtop Firemain for Test 3

4.3 Hydraulic Resistance Logic

Hydraulic resistance logic consists of closing a valve when the hydraulic resistance of the downstream piping is less than the setpoint. Hydraulic resistance is defined as follows:

$$R_H = P_D / Q^2 \quad (4)$$

where R_H = hydraulic resistance, psi/gpm² (Pa/lpm²)
 P_D = downstream pressure, psig (Pa)
 Q = flow rate, gpm (lpm)

The results of the screening evaluation [1] indicated that hydraulic resistance logic may be a reliable indicator of a rupture and warranted further investigation. Subsequent work has improved the understanding and capabilities of hydraulic resistance logic. For this study, the following key features are applied based on the rupture path logic methodology described in [25]:

1. Pressure Monitored at Smart Valve Inlet and Outlet. Pressure is monitored at the inlet and outlet of each smart valve.
2. Low Pressure Fault Threshold. A low pressure threshold is established to identify fault conditions for the system. When pressure decreases below the threshold, fault conditions are established and a time delay is triggered for valve closure (but the valve does not necessarily close).
3. Differential Pressure Measurement. The difference between the inlet and outlet pressure is monitored to determine the flow direction and the change in flow rate. If the differential pressure increases above a setpoint when the pressure decreases below the low pressure fault threshold, the valve is on the rupture path. The pressure decrease and differential pressure increase can be correlated with rupture hydraulic resistance conditions.
4. Closure Priority Schedules. If the pressure and differential pressure measurements indicate that the valve is on the rupture path, a time delay for closure is initiated. The time delay applied is a function of the distance from the operating pump (i.e., the number of smart valves which separate the pump from the particular smart valve), the closure time of the valve, and the type of rupture path⁵.
5. Time Delay Reset. If the differential pressure decreases below the setpoint or if the pressure increases above the threshold, the valve does not close and the time delay resets.

⁵ The method to establish closure priority schedule is currently being evaluated by MPR Associates and NRL for a patent under the title "Rupture Path Logic for Reflexive Isolation of Fluid Systems [25]. A description of the logic is provided in Appendix A of this report.

The adaptation of the hydraulic resistance logic described above has been tested on the benchtop model. The results from three tests are summarized in this report⁶. The test alignments can be classified as follows:

- Test 4: Rupture with no system degradation
- Test 5: Rupture with one valve disabled open and system hydraulic imbalance
- Test 6: Rupture with one valve disabled open and partial flow blockage

The test alignments are shown in Tables 6, 7 and 8. The results are shown in Figures 8, 9, and 10. The results of the comparison with the evaluation criteria is summarized below:

Capability to Isolate a Rupture with Hydraulic Resistance Logic

Along the rupture path, pressure decreases below and flow increases above values experienced during normal startup of service demands. Under rupture conditions, valves furthest from the pump are nearest the rupture. Based on these fundamentals and the results of the benchtop tests, hydraulic resistance logic can be used to isolate a rupture reliably with a minimal number of valve operations and without isolating intact piping sections. For tests 4, 5 and 6, two to four valve operations were required, and no intact piping sections were isolated. Compared to the low pressure logic, the reduction in number of required valve closures and the reduction in number of intact piping segments isolated is inherent in the fundamentals of the logic. In particular, the pressure, flow rate, flow direction and distance from the operating pump is a sufficient set of information to detect and locate the rupture. As such, the logic can successfully isolate a rupture for a wide variety of firemain designs and conditions.

Hydraulic resistance logic can be applied to any firemain architecture and combination of service demands. Ruptures in both large and small diameter pipe can be detected if smart valves are appropriately located.

Failure Modes and Limitations with Hydraulic Resistance Logic

Hydraulic resistance can successfully isolate a rupture with multiple valve and pump failures. Hydraulic resistance logic improves upon low pressure logic since it can distinguish between a pump trip and rupture.

Hydraulic resistance logic is susceptible to reduced performance if inaccurate information is processed by the smart rupture valve. Redundant smart valves compensate

⁶ A total of 7 test runs were performed using hydraulic resistance logic. Two test runs were performed with a rupture and no system degradation; two tests runs were performed with a rupture and one valve disabled open; two tests runs were performed with a pump trip; and one test was performed with a rupture and three valves disabled open. Three tests are shown which represent a cross-section of the results for optimal and non-optimal valve sequences. For all rupture test runs, the rupture was isolated and intact pipe segments were not isolated. For pump trip tests, all valves remained opened.

for malfunction in pressure and differential pressure measurement at any one valve. If the pump or valve status information available to a smart valve is inaccurate before the rupture, "non-optimal" rupture isolation may result. A non-optimal rupture isolation sequence will restore system operation but the number of valve closures may be greater than minimum and intact firemain segments may be isolated. Additional investigation may identify improvements to compensate for this degradation mechanism.

Another degradation mechanism is caused by excessive degradation of the flow measurement. For firemain systems, degradation in flow measurement accuracy is expected for many commercial technologies because buildup of biofouling product on the inside surface of the pipe is common. While this approach provides some margin for degradation, excessive degradation could result in valve closure when a large service load and insufficient pumps are operating. Additional testing and evaluation is underway to determine the significance of flow measurement degradation on the reliability of the logic.

Application of Commercial Technology with Hydraulic Resistance Logic

Hydraulic resistance logic can be implemented using components which are available commercially. Device communication technology is available from several commercial suppliers. Pressure and flow sensors are available from numerous suppliers. A concept valve is currently under development to support the DC-ARM program using a butterfly valve with pressure sensors embedded in the valve body inlet and outlet.

Table 6
Input and Initial Conditions for Test 4 Using Hydraulic Resistance Logic on the
Benchtop Model

Low Pressure Threshold:	10 psig
High ΔP Setpoint:	2 psi
Valve Time Delay: 5 seconds for 7 valve separation between pump and valve 10 seconds for 6 valve separation 15 seconds for 5 valve separation 20 seconds for 4 valve separation 25 seconds for 3 valve separation 30 seconds for 2 valve separation 35 seconds for 1 valve separation 40 seconds for 0 valve separation	
Pump Operation:	Manual
Initial Pump and Valve Alignment: V1 to V8 open P1, P6 operating	
System Degradation None	
Rupture Location: Between V4 and V6	

Table 7
Input and Initial Conditions for Test 5 Using Hydraulic Resistance Logic on the
Benchtop Model

Low Pressure Threshold:	10 psig
High ΔP Setpoint:	2 psi
Valve Time Delay: 5 seconds for 7 valve separation between pump and valve 10 seconds for 6 valve separation 15 seconds for 5 valve separation 20 seconds for 4 valve separation 25 seconds for 3 valve separation 30 seconds for 2 valve separation 35 seconds for 1 valve separation 40 seconds for 0 valve separation	
Pump Operation:	Manual
Initial Pump and Valve Alignment: V1 to V8 open P4, P6 operating	
System Degradation V4 is disabled open. Hydraulic resistance in main loop is imbalanced so that the flow rate through V6 is much greater than the flow rate through V2. Some of the flow from P4 is routed through V8. The imbalance is caused by the pump alignment and the differences in loss coefficients for loop valves and pipe segments. This imbalance is considered representative of some shipboard firemain.	
Rupture Location: Between V4 and V6	

Table 8
Input and Initial Conditions for Test 6 Using Hydraulic Resistance Logic on the
Benchtop Model

Low Pressure Threshold:	10 psig
High ΔP Setpoint:	2 psi
Valve Time Delay: 5 seconds for 7 valve separation between pump and valve 10 seconds for 6 valve separation 15 seconds for 5 valve separation 20 seconds for 4 valve separation 25 seconds for 3 valve separation 30 seconds for 2 valve separation 35 seconds for 1 valve separation 40 seconds for 0 valve separation	
Pump Operation:	Manual
Initial Pump and Valve Alignment: V1 to V8 open P1, P6 operating	
System Degradation V4 is disabled open. Hydraulic resistance in main loop is imbalanced so that most initial flow discharges from the rupture through V4 only. The imbalance is attributed to a small amount of trapped air near V6. This imbalance is not considered representative of shipboard firemain but is possible if flow is partially blocked due to biofouling buildup.	
Rupture Location: Between V4 and V6	

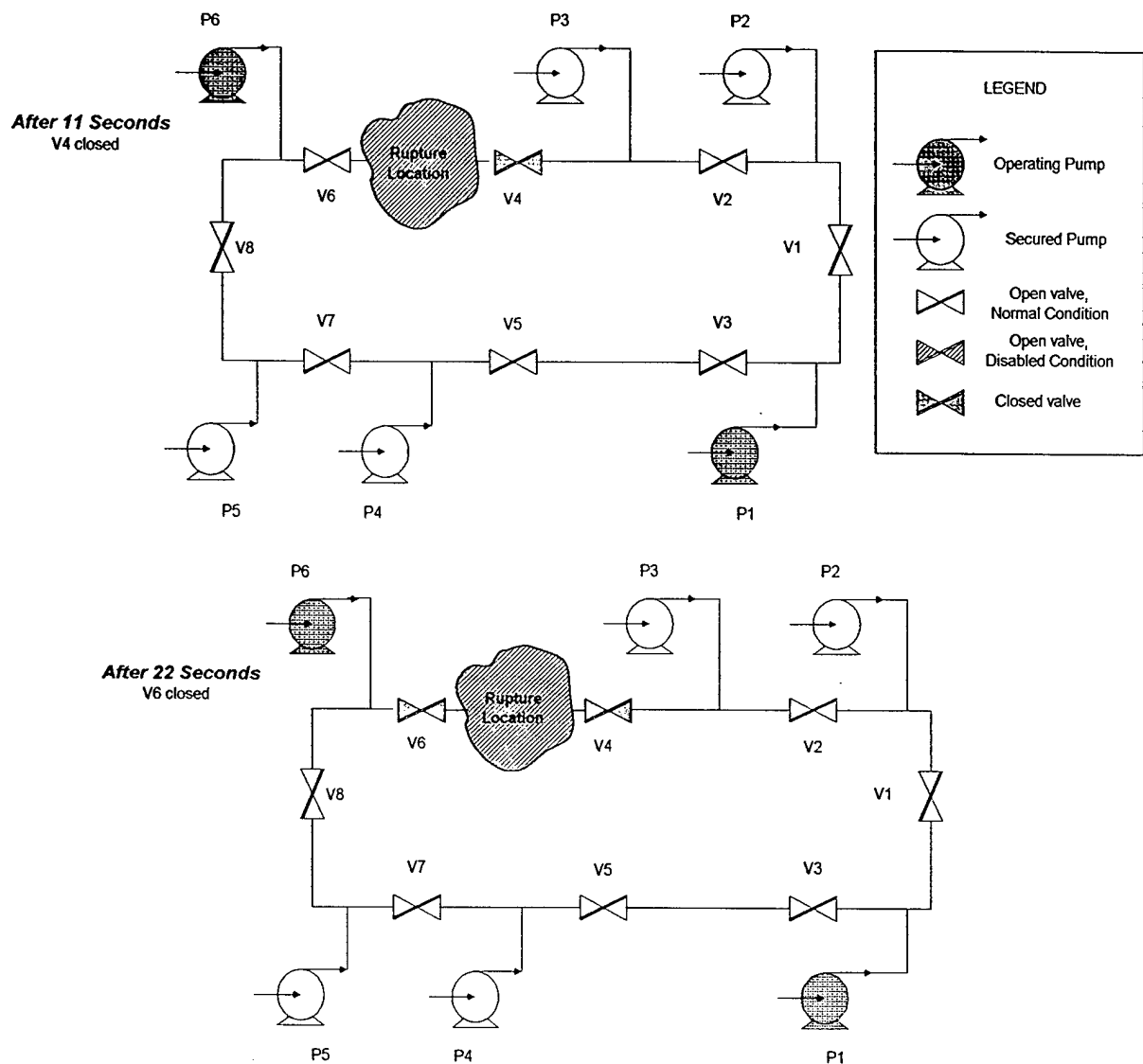


Figure 8. Results of Rupture Isolation For Test 4 Using Hydraulic Resistance Logic on the Benchtop Firemain

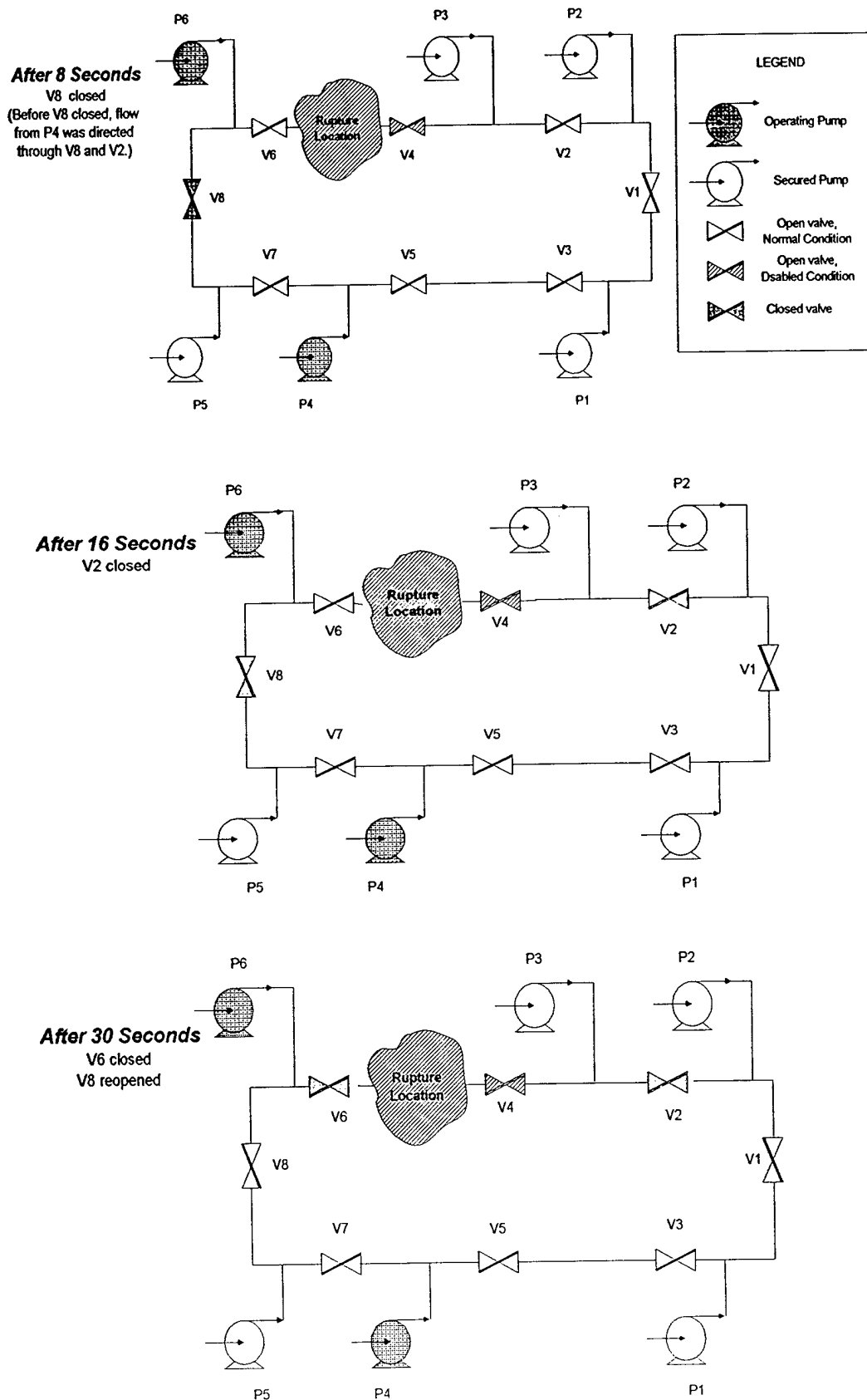


Figure 9. Results of Rupture Isolation For Test 5 Using Hydraulic Resistance Logic on the Benchtop Firemain

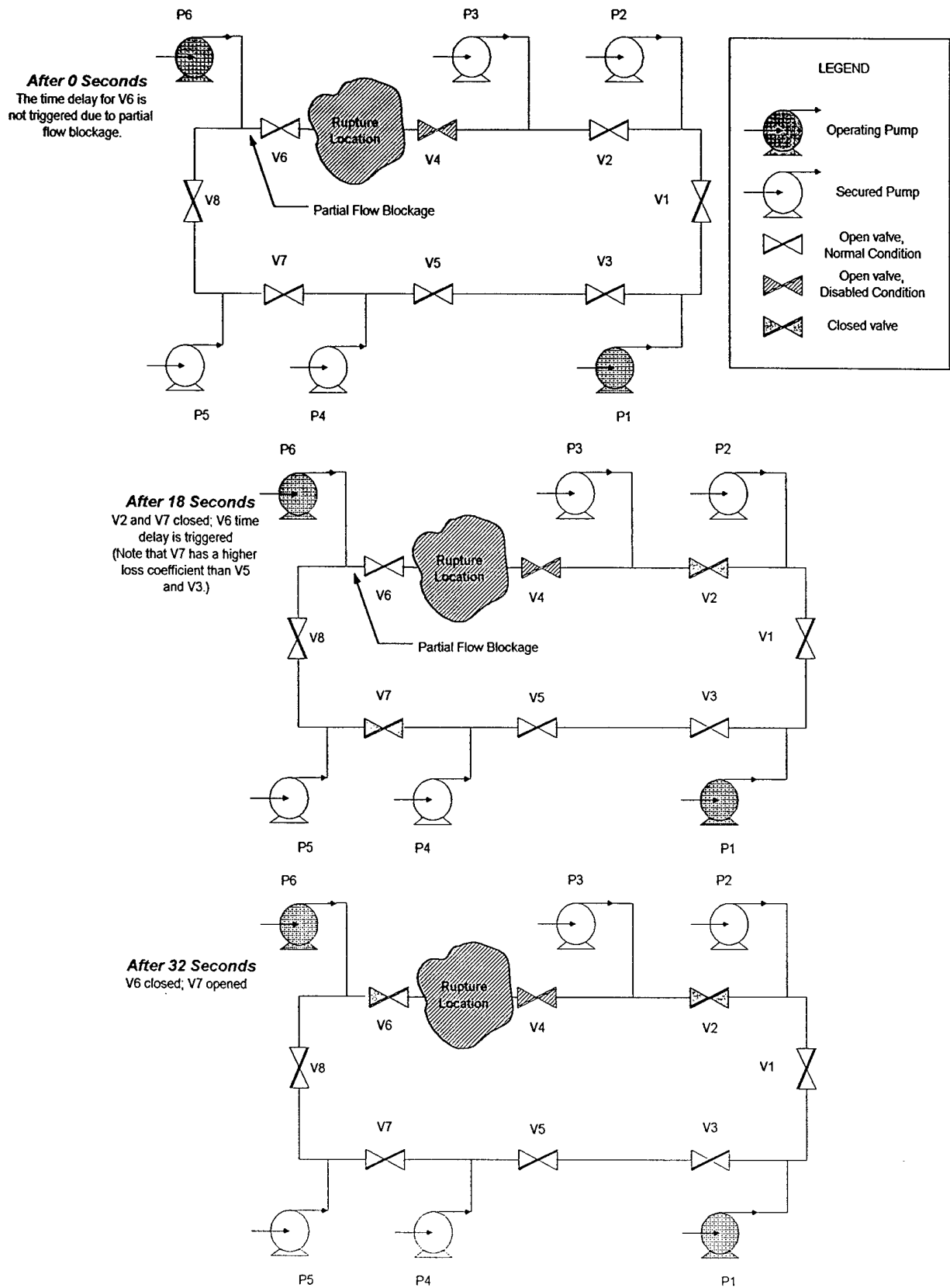


Figure 10. Results of Rupture Isolation For Test 6 Using Hydraulic Resistance Logic on the Benchtop Firemain

4.4 Flow Inventory Logic

Flow inventory logic consists of applying mass, momentum and energy conservation principles to segments of piping system volumes. As discussed in section 4.1, pipelines leak detection systems use static (steady state) and dynamic (transient) analysis methods to locate leaks. For a firemain, steady state analysis is sufficient to detect leaks and ruptures since water temperatures and volumes remain relatively constant.

A method to apply steady state flow inventory logic for a shipboard firemain is outlined in [1]. Mass imbalance is detected by summing supply and demand flow rates into sections of the system. If the residual flow rate (i.e., difference between the supply and demand flow rates) is greater than a set point limit, a rupture exists. The set point can be established based on uncertainty of the flow measurements. The flow balance for a pipe segment bounded by N smart valves is given by:

$$r_Q = \sum_{i=1}^N Q_i \quad (5)$$

where r_Q = flow balance residual between smart valves, gpm (lpm)
 Q_i = flow rate in one pipe segment, gpm (lpm)

The uncertainty in the flow balance measurement based on traditional root-sum-squares approach, in [26], is given by:

$$\delta Q_{Total} = [\sum_i^N \delta Q_i^2]^{1/2} \quad (6)$$

where δQ_i = uncertainty in flow measurement of one instrument

If the setpoint is selected as the uncertainty limit, the size of a detectable leak or rupture is based on the number of branches within a firemain section and the accuracy of each flow measurement.

NSWC Carderock Code 825 has been developing a "modified" flow inventory logic as part of the FRMS and ASR programs. A demonstration of the logic concept was performed as part of the DC-ARM demonstration testing in September 1998. The following key features were applied:

1. Monitor Differential Pressure Across Smart Valve. The differential pressure across smart valves are monitored to determine flow direction and rate.
2. Device Network Communication. Commercial device network communication is provided between neighboring smart valves using the LonWorks protocol.
3. Differential Flow Setpoint. Differences in flow direction and rate are evaluated at neighboring smart valves. Differences in flow rate above a setpoint indicate a rupture between the valves and the valves close.

The demonstration of the flow inventory logic on the SHADWELL was performed by simulating a rupture between valves 1-16-1 and 1-20-1. Fireplug 1-17-1 was used as the rupture flow path. (See Figure 11.) The input and initial conditions for the demonstration are listed in Table 9:

Table 9
Input and Initial Conditions for Demonstration of Flow Inventory Logic on the SHADWELL Firemain

Differential Flow Setpoint: Approximately 50 gpm (which corresponds to 0.5-1.0 inches H ₂ O)
Initial Flow Conditions: No flow
Rupture Flow Rate: Approximately 90 gpm
Initial Pump and Valve Alignment: 1-16-1 and 1-20-1 open Fire pump 1 operating Fire pump isolated from test valves by closing 1-27-5, 2-19-1 and 2-16-3
Rupture Location: Fire plug 1-17-1

During the demonstrations, the rupture flow rate was isolated by closing valves 1-16-1 and 1-20-1 approximately one minute after the rupture was initiated. (The closure time of the valves is greater than 30 seconds.) The results of the comparison with the evaluation criteria is summarized below:

Capability to Isolate Rupture with Flow Inventory Logic

Leaks in the fluid system can be accurately detected using an evaluation of mass balance for each pipe segment. Based on commercial pipeline leak detection technology, leaks greater than 3 gallons/hour are detected. Based on the logic methods demonstrated on the SHADWELL and the commercial pipeline technology, the rupture can be isolated with a minimum number of valve closures without isolating intact sections.

Failure Modes and Limitations with Flow Inventory Logic

Flow inventory logic requires communication. If communication between neighboring smart valves is lost, logic other than flow inventory logic is needed to isolate the rupture. As a result, flow inventory logic alone is inadequate for a survivable reflexive firemain system.

Commercial leak detection systems typically are inoperable if a measurement station fails or if the central computer is lost. If a reflexive smart valve malfunctions (without fluid system damage), isolation of intact firemain segments is possible. If a smart valve is lost following a weapons hit, a rupture may not be detected or isolated. Logic to accommodate malfunction or loss of a smart valve has not been developed and demonstrated. Initial assessment indicates that this logic will likely be complicated and will involve supervisory control input. For example, if the loss of a smart valve is detected, a mass balance could be performed on a larger segment of the firemain. The accuracy of the mass balance is reduced and the amount of configuration data stored on each valve increases geometrically.

Degradation in flow measurement accuracy is expected in firemain systems using many commercial technologies because buildup of biofouling product on the inside surface of the pipe is common. Due to the potential for flow measurement degradation, substantial drift in mass balance setpoint is possible. Degradation in performance is expected to be more severe with flow inventory logic than with low pressure or hydraulic resistance logic because more instruments are needed. (Flowmeters or flow switches are needed in all branches.)

Application of Commercial Technology with Flow Inventory Logic

Flow inventory logic has been implemented in commercial pipelines as described in section 4.1. These systems are configured with a central supervisory station and remote measurement stations. This centralized approach would need to be modified for a reflexive shipboard firemain where more distributed, independent control points are needed to improve survivability. One approach for adapting commercial pipeline mass balance systems is to install central supervisory logic at each smart valve. While this is possible with some embedded processors, this approach is complicated because the amount of software embedded at each smart valve is large and because development of the software which interfaces between neighboring smart valves is needed. Another approach for implementing flow inventory logic is to develop simplified device level logic which is embedded at each valve. This is the approach which NSW/C Carderock Code 825 is pursuing. In addition, considerable additional software development may be needed to address the loss of a smart valve as discussed above.

LEGEND

Z	Zebra Valve
FP	Fire Plug
	Open valve, Normal Condition
	Closed valve
	Motor
	Operated Valve

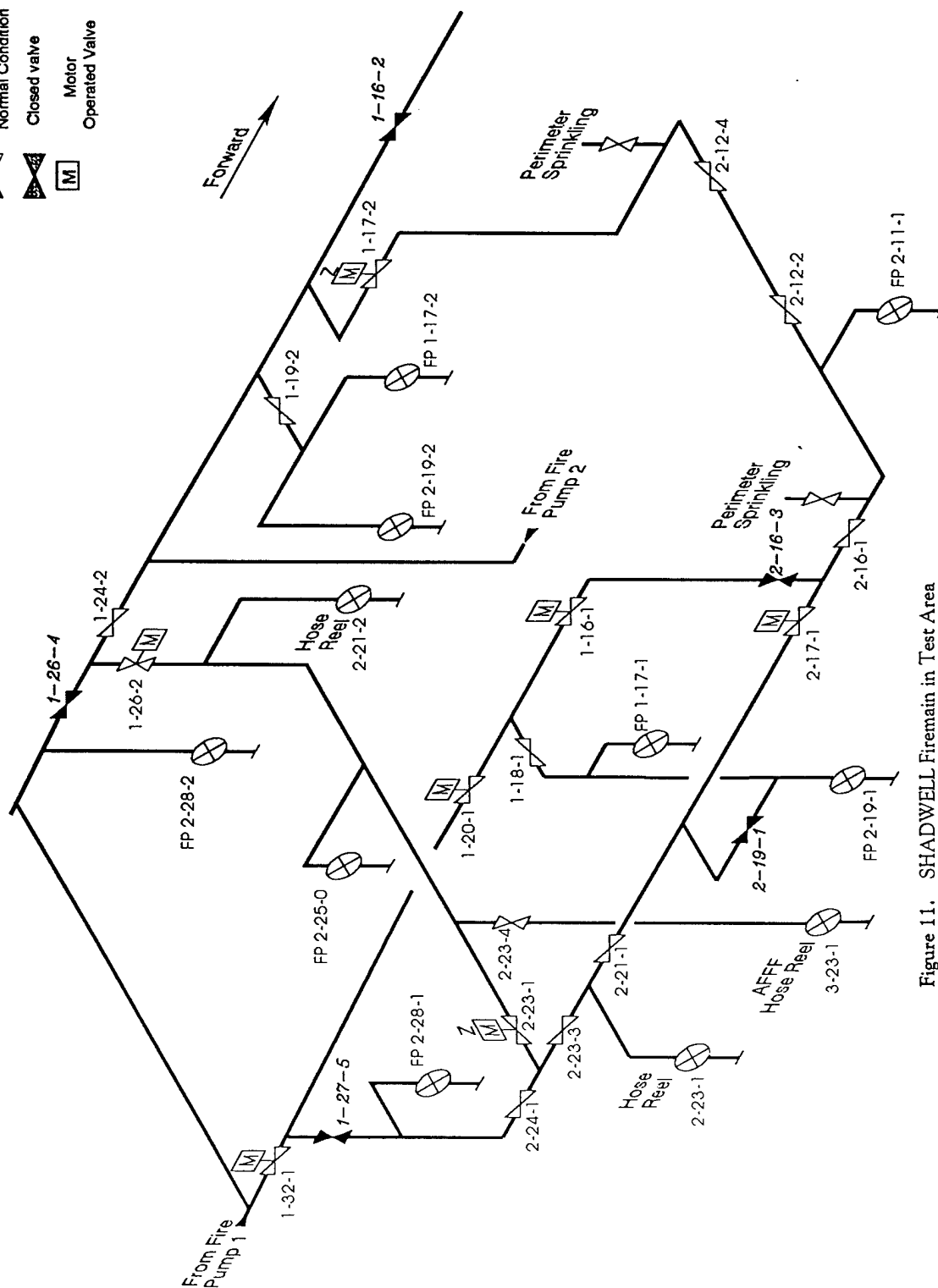


Figure 11. SHADWELL Firemain in Test Area
Showing Valve Line-Up for Rupture Simulation Using Flow Inventory Logic

4.5 Rupture Signal Detection Logic

Fluid system acoustic pressure and pipe vibration data may be used to detect a rupture or other damage to fluid systems. However, data currently available is insufficient to assess and compare the characteristics of a rupture from other hydraulic transients such as a water hammer, pump trips and valve opening. If pressure and vibration data indicate that characteristics associated with a rupture are unique, then it may be possible to develop fluid system rupture detection logic and associated threshold criteria. This logic could be implemented on a microprocessor embedded in a smart valve. If data measured by sensors embedded in the valve body and evaluated by the microprocessor is characteristic of a rupture, the valve would close based on a priority schedule programmed in the microprocessor. Rupture signal detection logic could be added or "layered over" other rupture logic methods such as low pressure or hydraulic resistance to improve reliability.

Testing to measure baseline hydraulic transient and rupture data is being conducted on a firemain installed at Aberdeen Proving Grounds as part of the Automated Systems Reconfiguration Program (ASR) performed by NSWC Carderock and Dahlgren. Pressure transducers and accelerometers are installed at four measurement stations each at a different distance from the rupture location. Instrumentation selected is similar to pressure transducers used in commercial acoustic monitors for pipeline leak detection and accelerometers used in commercial equipment vibration monitors for condition based maintenance. Weapons detonations will be used to create a rupture. Some preliminary data has been measured but the testing is incomplete, and data analysis has not been performed yet.

Based on the data measured at Aberdeen, a suitable approach to develop a rupture signal detection system at a smart valve may be identified. Implementation of one or more the following methods may be considered feasible:

- **Pressure or Acceleration Thresholds.** If the fluid pressure or pipe acceleration during a rupture is greater than during other hydraulic transients, an absolute threshold may be used to detect rupture conditions. Alternatively, rate of change calculations for the pressure or vibration data may detect differences between rupture energy release and other hydraulic transients.
- **Frequency Domain Attributes.** Data from a rupture may have a different signature in the frequency domain than data from other hydraulic transients. Performing Fourier or Wavelet transforms, it may be possible to detect a rupture using thresholds set at certain frequencies.
- **Pattern Recognition.** Using the rupture and non-rupture transient test data, pattern recognition software could be embedded in the smart valve to distinguish between rupture and non-rupture conditions.

Capability to Isolate a Rupture with Rupture Signal Detection Logic

It is not known if a rupture can be detected using rupture signal detection logic. While it is expected that the pressure pulse from a rupture can be distinguished from other transients, it is unclear if the location can be determined.

Failure Modes and Limitations with Rupture Signal Detection Logic

The data available is insufficient to determine failure modes and limitations.

Application of Commercial Technology with Rupture Signal Detection Logic

Development of rupture signal detection methods has more risk and requires more time than other logic methods discussed in this report. In particular, rupture and non-rupture transient data needs to be analyzed, a suitable detection method needs to be developed and a concept valve needs to be fabricated and tested. Several years of development are probably needed before a prototype valve with rupture signal detection logic would be ready for prototype shipboard installation. As such, this method may be best suited as a potential future addition to improve the reliability of other methods which might be ready for shipboard installation earlier.

5.0 Conclusions

The hydraulic resistance logic is the most cost effective core logic to carry forward for continued DC-ARM development and demonstration. The most important attribute of hydraulic resistance logic is the ability to isolate a rupture without the need for communication between firemain system components after damage. The logic is fairly simple and tolerant of component failures and sensor inaccuracies. Commercial components are available to implement the hydraulic resistance logic. The engineering development needed is considered low risk and within the scope of the DC-ARM program.

Low pressure logic is simple to implement, but isolation of intact segments of the firemain is likely. Restoring service to intact segments would require either communication after damage or valve sequencing that could cause intermittent (and dangerous) interruptions in firemain service during active firefighting. In addition, enhancements would have to be developed to prevent firemain failures during non-damage operational problems such as temporary shutdown of the fire pumps. Therefore, low pressure logic, alone, is not recommended for further development in firemain applications.

Flow inventory logic could, under ideal conditions, provide accurate leak detection and isolation. However, it depends upon communication between firemain components after damage. In addition, it is not inherently tolerant of component failures. The enhancements to make flow inventory logic tolerant of component failures are likely to result in a complex system, with the associated burdens of reduced reliability and increased life-cycle costs. In addition, flow inventory logic would not be tolerant of reductions in sensor accuracy over time. Therefore, flow inventory logic is not considered suitable as the core logic for a reflexive firemain. Flow inventory logic could be added as an enhancement to a reflexive valve with a core logic based on hydraulic resistance. This could provide for a faster response, isolation of smaller leaks, and reduce the chance of isolating an intact pipe segment as long as communication between neighboring reflexive valves remained intact after damage. These enhancements to hydraulic resistance logic are not considered necessary at this time to meet the DC-ARM goals. Results from the ASR tests of flow inventory logic will be reviewed. If continued development indicates that the hydraulic resistance logic may not, by itself, meet the DC-ARM goals, flow inventory logic will be considered as an enhancement to address such deficiencies.

Rupture signal detection lacks the basic information needed to characterize a firemain rupture in a weapon hit environment. This information is needed to determine if this approach can be used, to determine if commercial components are available to support the approach, and to develop appropriate algorithms. In addition to the unforeseen technical issues which would need to be resolved, the time and cost needed to develop rupture signal detection logic is estimated to be greater than with hydraulic resistance logic. Therefore, rupture signal detection logic is not considered suitable as the core logic for reflexive firemain valves. Rupture signal detection capability could be added as an enhancement to improve the reliability of hydraulic resistance logic.

The conclusions and recommendations for reflexive firemain valve logic methods are shown in Table 10. Based on this evaluation, the shipboard installation of a reflexive firemain is planned for the ex-USS SHADWELL using the following approach to implement hydraulic resistance logic:

1. Determine the pump head-flow characteristic, flow rates for ruptures and flow rates for vital loads. Determine the operating requirements for the pumps and system operating pressures.
2. Identify the minimum rupture size to be detected. This would depend on the size of the rupture that can be tolerated without degrading system performance to an unacceptable level.
3. Identify suitable locations for smart valves and type of hydraulic resistance logic (absolute or relative). Factors considered when identifying smart valve locations are the location and number of firemain segments needed to support damage control and recovery operations and the minimum rupture size.
4. Identify pressure and flow setpoints for the reflexive valves. This requires a review of firemain pressures and flow rates for both normal intact conditions and for rupture conditions

5. Determine closure priorities and time delays for the reflexive valves. This requires that the time to restore firemain service be identified and rupture path logic be applied. Based on the results of the DC-ARM tests [8], six minutes is a suitable recovery time for a firemain.
6. Identify smart valve and actuator models. Based on the closing time of the valve/actuator combination and the location of the pumps and smart valves, identify the priority for closure time delays.
7. Develop a set of pump logic based on the firemain design and the operating requirements of the electrical plant. Pump logic is a function of the flow demand and is not needed for rupture isolation when more than one pump is operating.

Table 10
Conclusions and Recommendations for Reflexive Firemain Valve Logic Methods

Logic Method	Conclusions	Recommendations
Low Pressure	Simple to implement. Does not pinpoint rupture location. Enhancements needed for acceptable performance	<i>Do not adopt as core logic.</i> Implement as part of hydraulic resistance logic
Hydraulic Resistance	Detects and locates a rupture without communication between components following damage.	<i>Adopt as core logic for firemain reflexive valves.</i> Develop and test concept valve.
Flow Inventory	Accurate detection and location of leaks. Complex to implement considering communication failure or loss of a reflexive valve.	<i>Do not adopt as core logic.</i> May be used to enhance hydraulic resistance logic.
Rupture Signal Detection	Data is incomplete. Cost and effort to develop is high.	<i>Do not adopt as core logic.</i> May be used to enhance hydraulic resistance logic.

This method of implementation is independent of the firemain architecture and can be applied to other shipboard firemain systems. As a result, the shipboard fluid system design can be developed based on system performance requirements, human system integration, cost, maintenance and other factors. The reflexive system operation can be added later in the design process. Application of the results of this study to fluid systems other than the firemain is planned. In general, the approach consists of

1. Develop a baseline architecture based on current shipboard design practices.
2. Identify the operating requirements for the fluid system (including minimum detectable leak size, required time to restore system operation, number of operating pumps and vital system demands)
3. Select candidate reflexive valve logic methods based on the operating requirements and the results of this evaluation. For a fire suppression system, the candidate logic methods will probably be the same as for the firemain. For a fuel service system, additional monitoring methods such as boundary monitoring will be selected.
4. Evaluate candidate logic methods using the same evaluation criteria described in this report. Testing is not planned for this evaluation; instead, the results from this report

will be used to identify the most suitable combination of logic methods to meet the operating requirements for these systems.

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Appendix A

Description of Rupture Path Logic

This appendix contains a description of the hydraulic resistance logic used in the benchtop tests. This description is from the invention disclosure for rupture path logic [25].

TITLE OF INVENTION: Rupture Path Logic for Reflexive Isolation of Fluid System Ruptures

PURPOSE

Rupture path logic is a method which automatically detects and isolates a pipe rupture or other large leak of any piping system with a pressurized source of fluid (such as a pump or tank). Rupture path logic is implemented by embedding algorithms in smart valves¹.

BACKGROUND

Most fluid systems are not equipped with automated components which detect and isolate ruptures². Where automated systems are installed to isolate leaks, one of the following two approaches are used:

- **Low Pressure Isolation.** Low pressure isolation consists of closing valves when the pressure in the system decreases below a set threshold. Valves which automatically close with low pressure are standard technology. The valves are inexpensive and can be operated without electrical power (such as with hydraulic and mechanical spring-loaded energy sources). The primary disadvantage of this approach is the inadvertent isolation of intact piping section following non-rupture upset conditions including loss of electrical power and pump malfunctions.
- **Leak Detection.** Commercial leak detection technology typically consists of measuring flow at multiple locations in a piping system and calculating a mass balance. If the mass imbalance is greater than a set threshold, the leak is detected. The primary disadvantages with leak detection methods are (1) continuous communication between components in the piping system must be maintained to detect a rupture, (2) accurate flow measurement is required, (3) sensor malfunction is difficult and complicated to accommodate.

DESCRIPTION AND OPERATION

Rupture path logic was developed as comprehensive, high reliability and inexpensive logic to restore piping system operation following one or more pipe ruptures (with small or large piping). The method was developed using the characteristics of a Navy shipboard firemain system based on the initial evaluation described in Reference 1. The process of implementing rupture path logic for a particular application is an optimization trade-off based on the time for rupture isolation, size of leak isolated, valve closure times, and cost. Rupture path logic can be one of several building blocks used in smart valves. Other logic

¹ A smart valve contains onboard sensing, data processing, communication and valve actuation capabilities. A smart valve can operate automatically based on the conditions detected by the onboard sensors and the control logic embedded in the onboard data processor.

² A rupture is damage where a pipe segment separates into two parts or any other large leak where the hole in the pipe is greater than the transverse pipe area. Rupture path logic may detect and isolate smaller leaks, but the method was developed to isolate rupture events.

which may contain elements for condition based maintenance, other methods of leak detection, environmental monitoring, or other features can be readily added without impacting rupture isolation.

Required Inputs

To implement rupture path logic, the following inputs are required for the smart valve:

- pressures at the smart valve inlet and outlet,
- differential pressure across the smart valve,
- flow direction through the smart valve, and
- the locations of pressurized fluid sources relative to the smart valve (e.g., pump operating alignment).

Differential pressure measurement can be used to determine flow direction. Communications between smart valves and fluid system pressure sources are needed only prior to the rupture or damage event to identify the locations of the pressurized fluid sources.

Configuration Data Required for Rupture Path Logic

The following configuration data for rupture path logic is installed during initial setup (or following system tuning). This data can be embedded in each smart valve or provided by a supervisory control system.

Low Pressure Setpoint. At pressures less than the low pressure setpoint, the fluid system is in fault condition and action is needed to restore the system to normal operation.

High Differential Pressure Setpoint. The differential pressure setpoint corresponds approximately to the minimum rupture flow rate which can be detected. The setpoint can be an absolute threshold (a specific ΔP_{set}) or a relative threshold (ΔP increases a set proportion). If the high differential pressure setpoint is exceeded when the pressure decreases below the low pressure setpoint, the valve is on the rupture path.

Valve Location Tables. For each pump (or other pressurized source of fluid) and each possible flow direction, the location of the smart valve is identified. The location corresponds to the number of smart valves which separate the valve from the pressurized source.

Time Delay Closure Schedule. For each valve, a time delay is assigned. For valves located distant from the pressurized source (high location numbers), the time delay is short. For valves located near the source, the time delay is longer.

Rupture Isolation Sequence

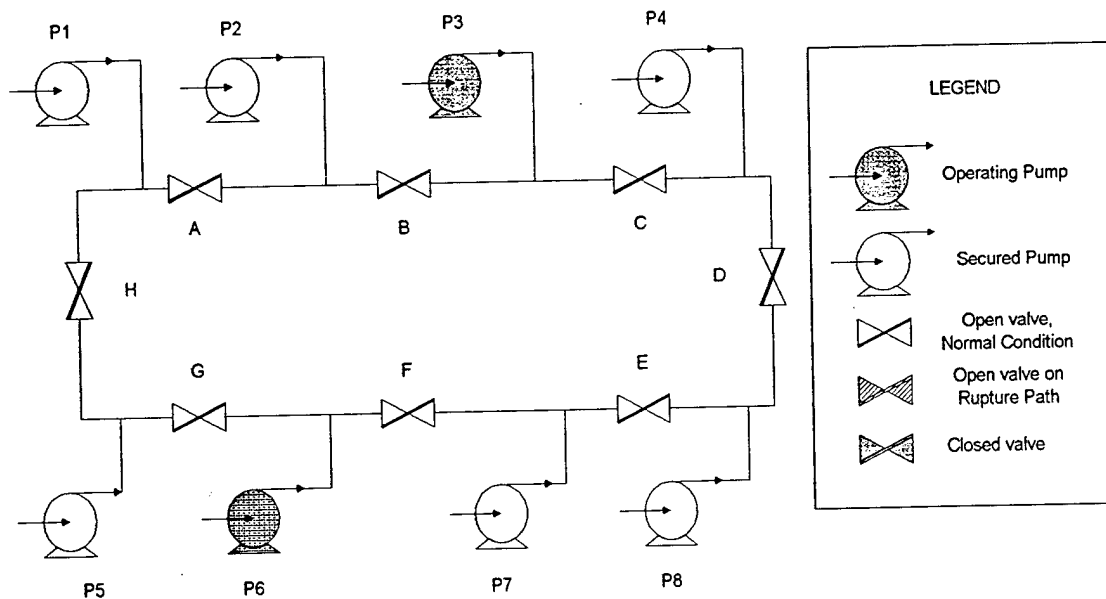
- 1) During normal operation (prior to a rupture or other damage event), each smart valve updates its data of the operating status of pressurized sources (e.g. pumps) and remains in its normal operating position.
- 2) When a rupture or other large leak occurs, flow through the system will increase along the primary rupture flow path from the pressurized sources towards the leak. The pressure at a valve in the primary rupture flow path will decrease, and the flow through the valve in the rupture flow path will increase. For valves that are not on the primary rupture flow path, pressure will decrease, but flow will not increase. Two pressure sensors (at the inlet and outlet of a smart valve) provide the necessary inputs (for absolute pressure and differential pressure) to determine the smart valve operation following damage.
- 3) A decrease in pressure and an increase in flow (detected by the associated increase in differential pressure) beyond set thresholds will indicate that the smart valve is on the rupture path. For the low pressure part of the logic, an absolute setpoint is used to determine that the system is in fault condition. For the high differential pressure part of the logic, a setpoint based on a relative increase can be used to determine if the valve is on the flow path. By using the relative increase approach, the necessary sensitivity of the pressure sensors is reduced because an exact flow measurement is not required. As a result, the reliability of the logic is improved because the setpoint is less sensitive to upstream flow disturbances (such as tees and elbows) and long term changes in flow characteristics due to fouling, biological growth, or other factors.
- 4) If the sensor inputs indicate a smart valve is on the primary rupture path, the rupture path logic will identify a closure schedule for the valve. The closure schedule is based on the flow direction through the smart valve and the associated smart valve location relative to the operating pressurized sources of fluid (e.g. pumps).
- 5) The smart valves close based on the closure schedule timing programmed into each smart valve. Smart valves located the farthest from the pressurized sources will close first. After a smart valve on the primary flow path closes, the flow through the system may change, causing flow along a secondary flow path. The increase in flow through valves along the secondary flow path triggers their logic to close after a pre-set delay. By correctly setting the closure timing schedules for the primary and secondary rupture paths, only the valves nearest the rupture location close.

- 6) Once the leak is isolated, pressure and flow in the system returns to normal. Normal pressure and flow is sensed by each smart valve, and additional closures are not needed as their condition returns to normal.

Note: The following three examples illustrate how rupture path logic isolates piping system ruptures. With these three examples, it is shown that rupture path logic can be applied to any pipe configuration since piping networks consist of combinations of these three. The logic shown in the examples have not been optimized. An actual system design arrangement and requirements would be needed to develop an optimized design.

Example 1: Rupture Isolation for a Simple Loop

Consider a loop piping system configuration with eight piping segments (such that each can be isolated), eight pumps, and eight smart valves similar to the offset loop design



described in Reference 1. The system is operating normally with Pump 6 (P6) and Pump 3 (P3) operating.

- 1) Consider a rupture at valve D.
- 2) The pressure in the loop will decrease below the low pressure setpoint and flow will increase through valves C, E, and F. The high differential pressure setpoint is exceeded for valves C, E and F indicating that they are on the primary rupture path. Based on the flow direction and operating pump alignment, the smart valve locations in Table 1 are determined by the rupture path logic.

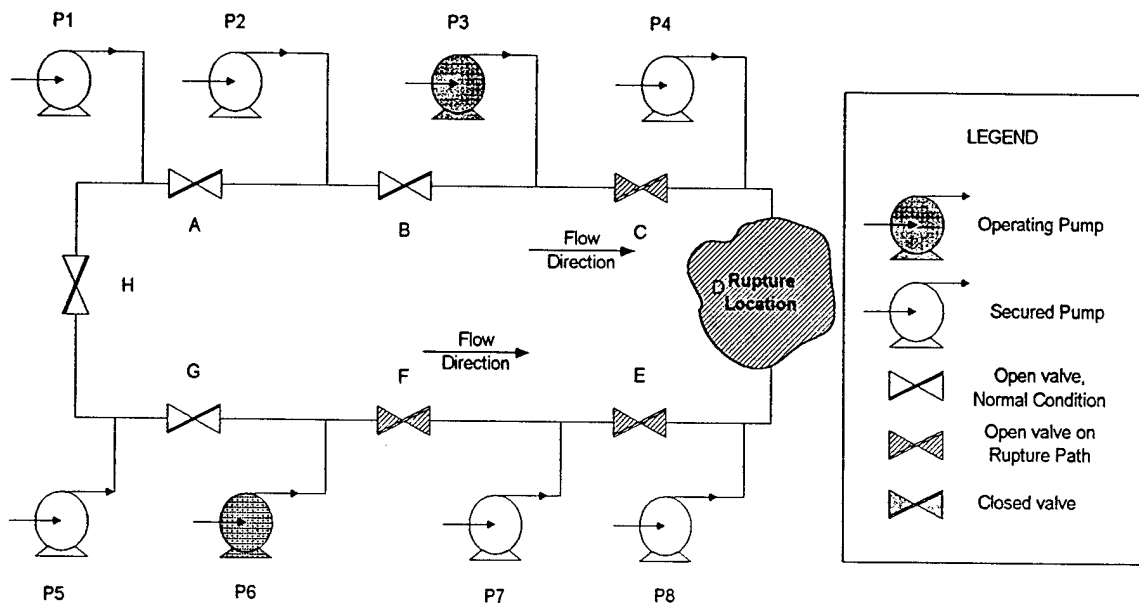


Table 1. Smart Valve Location on the Primary Rupture Path

Valve	Flow Direction ⁽¹⁾	Valve Location for Flow from Pump 3 ⁽²⁾	Valve Location for Flow from Pump 6 ⁽²⁾
C	Right	1	5
E	Right	6	2
F	Right	5	1

⁽¹⁾ The flow direction is relative to the valve based on its orientation shown in the figure above.

⁽²⁾ The valve location is the number of the smart valves from the operating pump in the direction of flow (i.e., valves are numbered sequentially one through eight in the direction of flow, with one being closest to the pump and eight being furthest from the pump).

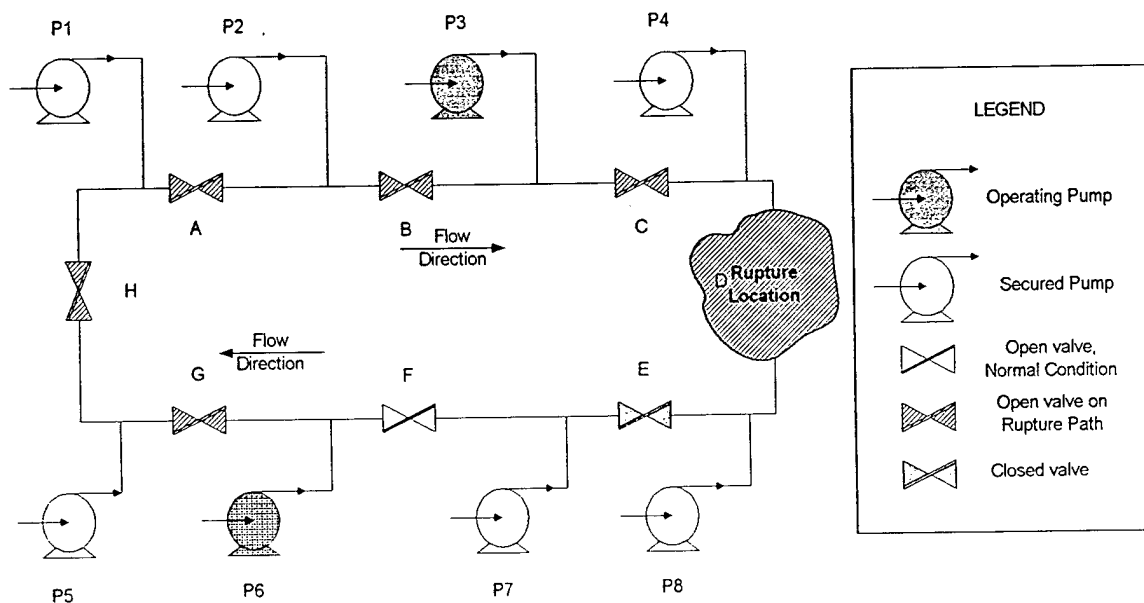
- 3) Upon determination that a smart valve is on the primary rupture flow path, a clock in the smart valve controller is started so that valve will close after a preset time delay. The preset time delay is a function of the location of the smart valve along the primary rupture flow path with respect to the operating pumps. See Table 2.

Table 2. Smart Valve Closure Time Delay for Smart Valves on Primary Rupture Path

Location	Time to Closure (sec)
8	5
7	25
6	45
5	65
4	85
3	105
2	125
1	145

With two pumps operating, two time delays are identified and the smart valve will close based the shortest of the two time delays.

- 4) Smart valves A, B, G and H sense a low pressure but the differential pressure decreases and therefore does not trip their setpoints. These valves are not on the primary rupture path. A trigger is tripped in these valves to indicate that they are not on the primary rupture path.
- 5) Based on Tables 1 and 2, valve E will close at 45 seconds following the rupture. Upon closure, differential pressure at valve F decreases below its setpoint, therefore the valve is not considered on the rupture path and its associated time delay clock is stopped.



- 6) After smart valve E closes, a secondary rupture flow path established when the flow from Pump 6 changes direction. Smart valves A, B, G and H sense an increase in differential pressure above their setpoints indicating that they are on the rupture path. Since the primary rupture path trigger is tripped, these valves use secondary rupture path logic. The valve locations for the valves on the secondary rupture path are shown in Table 3.

Table 3. Valve Locations for Smart Valves on the Secondary Rupture Path

Valve	Flow Direction	Valve Location for Flow from Pump 3	Valve Location for Flow from Pump 6
A	Right	7	3
B	Right	8	4
G	Left	5	1
H	Up	6	2

- 7) The clock is initiated for closure time delay for each of the smart valves on the secondary rupture path when the high differential setpoint is exceeded in accordance with Table 4.

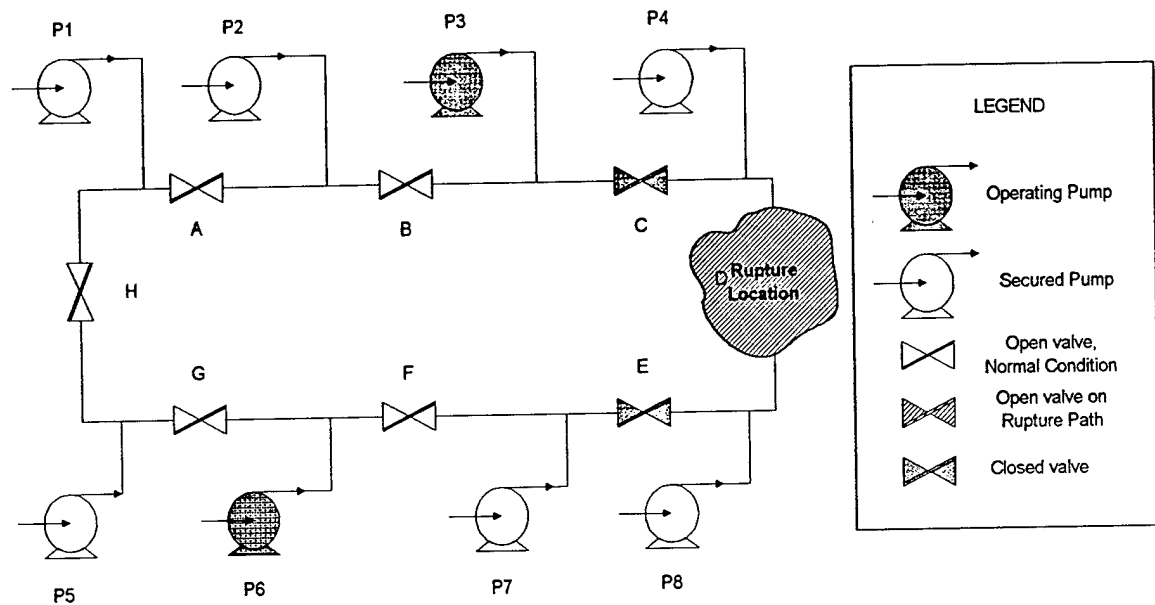
Table 4. Closure Time Delay for Smart Valves on Secondary Rupture Path

Location	Time to Closure (sec)
8	$5 + \delta$
7	$25 + \delta$
6	$45 + \delta$
5	$65 + \delta$
4	$85 + \delta$
3	$105 + \delta$
2	$125 + \delta$
1	$145 + \delta$

The secondary time delay constant, δ , is based on rupture isolation time requirements and pump operating alignment. For this example, consider $\delta = 60$ seconds. With two pumps operating, two time delays are identified and the valve will close with the lowest time delay.

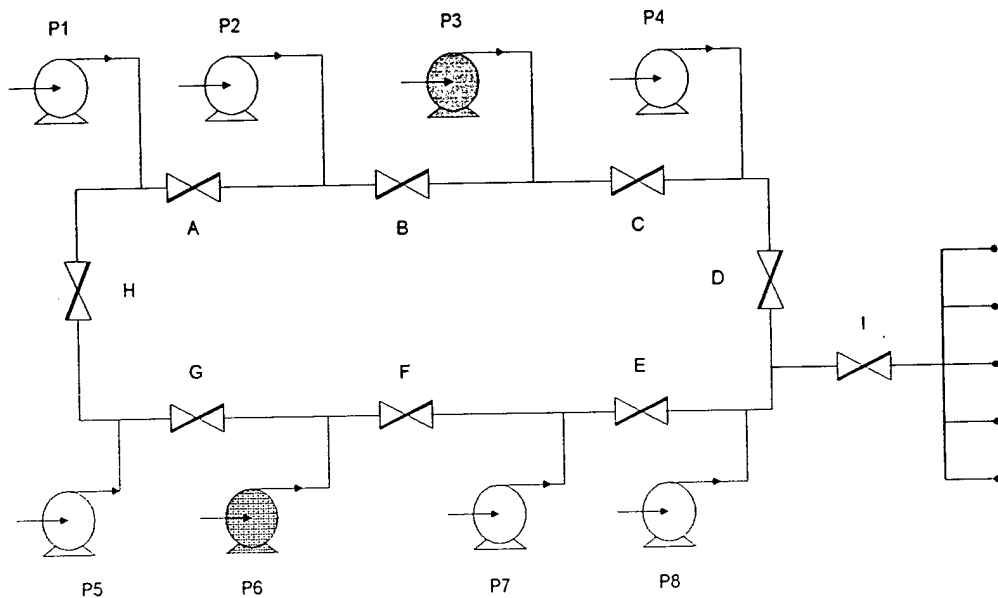
- 8) Based on primary rupture path logic in Tables 1 and 2, smart valve C will close after 65 seconds (or 20 seconds after the secondary rupture path is initiated), isolating the leak. At smart valves A, B, G, and H, the absolute pressure increases to normal values (above their setpoints), differential pressure decreases below their

setpoints, their associated time delay clocks are reset to zero, and their operating logic is reset to normal.

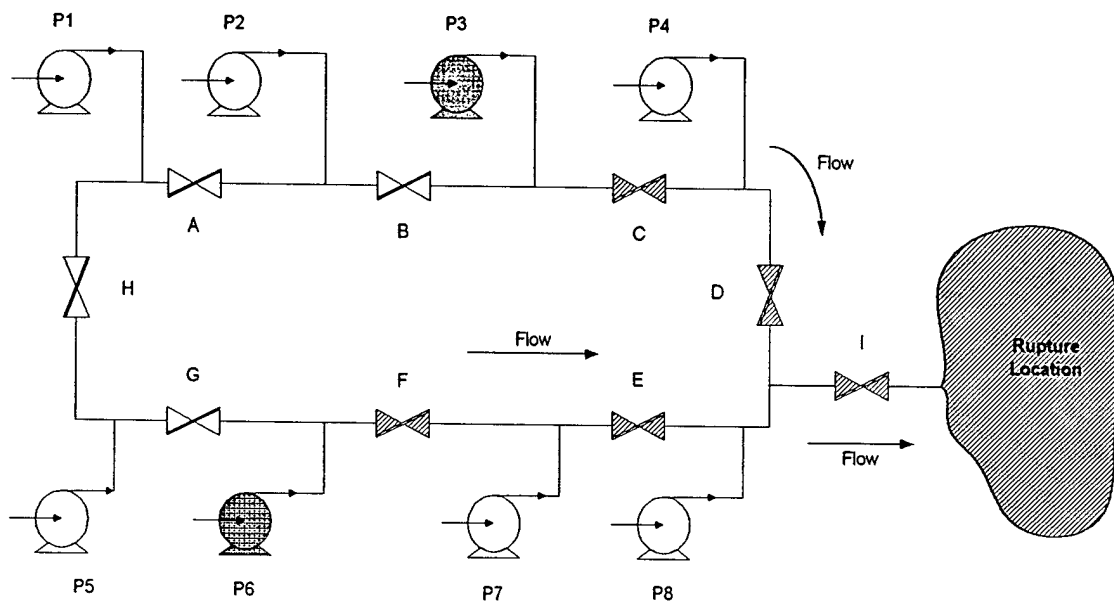


Example 2: Rupture Isolation for Branch Piping

Consider branch piping attached to the simple loop in Example 1. Pumps 3 and 6 are operating and all of the smart valves (valves A to I) are open.



- 1) A damage event ruptures the branch piping. The size of the rupture is large enough to reduce the pressure in the loop and differential pressure increases for valves C, D, E, F, and I. Based on their setpoints, Valves C, D, E, F, and I are on the primary rupture path.



- 2) The valve logic for the smart valves in the loop is the same as for Example 1. The valve locations are shown in Table 5 and closure time delays are shown in Table 6.

Table 5. Loop Valve Location on the Primary Rupture Path

Valve	Flow Direction ⁽¹⁾	Valve Location for Flow from Pump 3 ⁽²⁾	Valve Location for Flow from Pump 6 ⁽²⁾
C	Right	1	5
D	Down	2	6
E	Right	6	2
F	Right	5	1

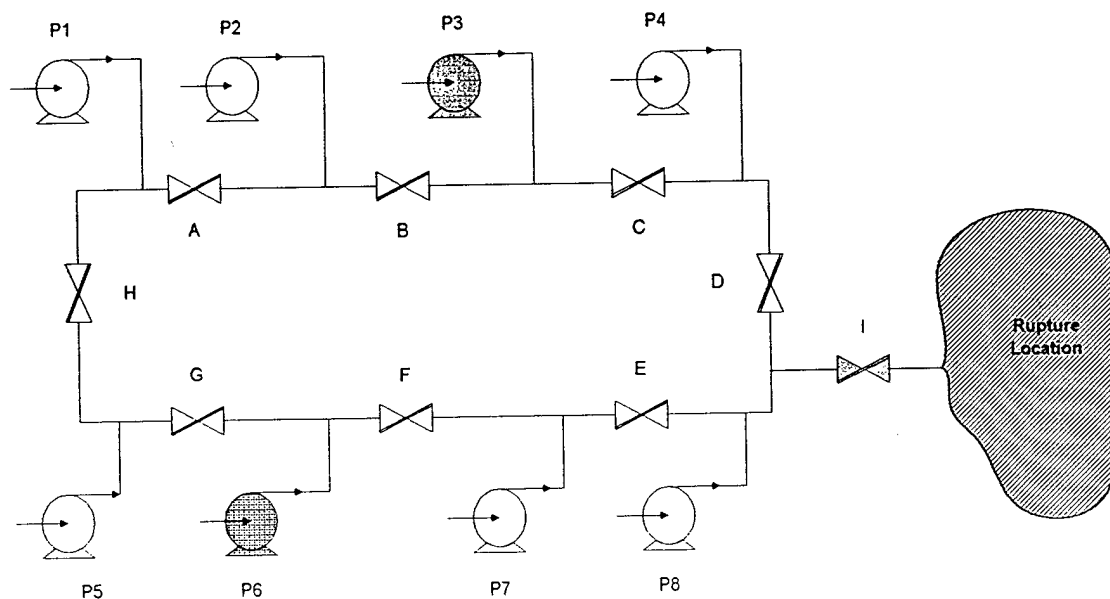
⁽¹⁾ The flow direction is relative to the valve based on its orientation shown in the figure above.

⁽²⁾ The valve location is the number of the smart valves from the operating pump in the direction of flow (i.e., valves are numbered sequentially one through eight in the direction of flow, with one being closest to the pump and eight being furthest from the pump).

Table 6. Loop Valve Closure Time Delay for Smart Valves on Primary Rupture Path

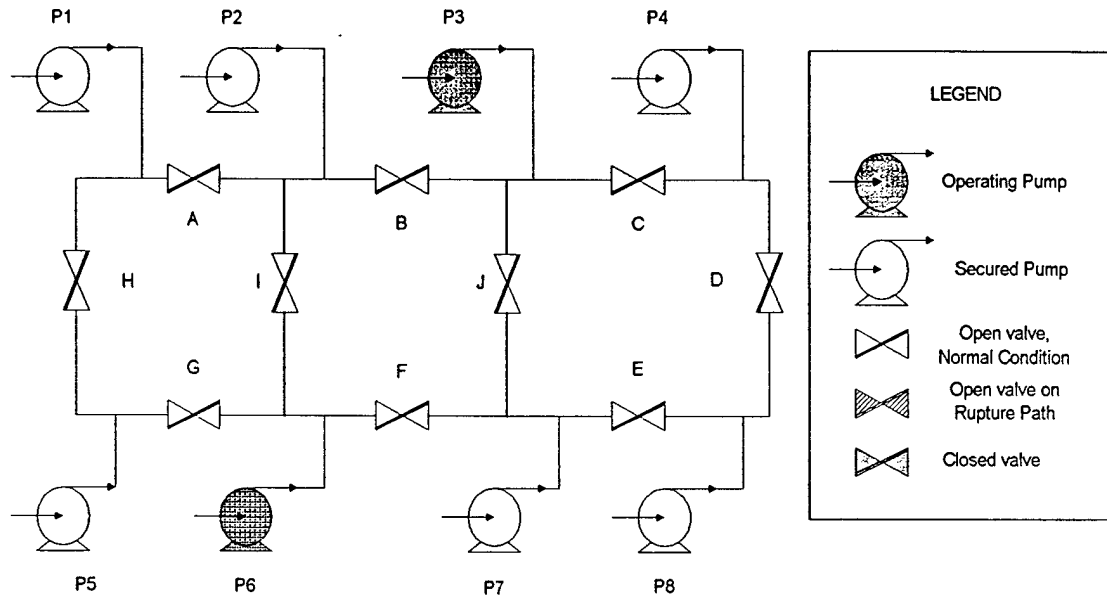
Location	Time to Closure (sec)
8	5
7	25
6	45
5	65
4	85
3	105
2	125
1	145

- 3) The logic for the branch valve I is different than for the loop valves. The pressurized source for branch valves is the pipe connection to the loop. Valve I is the only smart valve in the ruptured branch and therefore has a short time delay. For this example, a time delay of 5 seconds is applied.
- 4) Valve I closes after 5 seconds and isolates the leak. At smart valves C, D, E, and F, the absolute pressure increases to normal values (above their setpoints), differential pressure decreases below their setpoints, their associated time delay clocks are reset to zero, and their operating logic is reset to normal.



Example 3: Rupture Isolation for a Loop with Multiple Cross-Connects

Consider a loop piping system as in Example 1 with two additional cross-connects. The system is operating normally as shown below with Pump 6 (P6) and Pump 3 (P3) operating.



- 1) Consider a rupture at valve D.
- 2) The pressure in the loop will decrease below the low pressure setpoint and flow will increase through valves C, E, and F. The high differential pressure setpoint is exceeded for valves C, E and F indicating that they are on the primary rupture path. Based on the, flow direction and operating pump alignment, the smart valve locations in Table 7 are determined by the rupture path logic.

The rupture path logic used to determine valve location is different for this example than with Example 1. With multiple cross-connects, there are several different options available to determine the valve locations. For this example the lowest number of valves from the pump is selected. Using this numbering convention, the highest possible location number is 5.

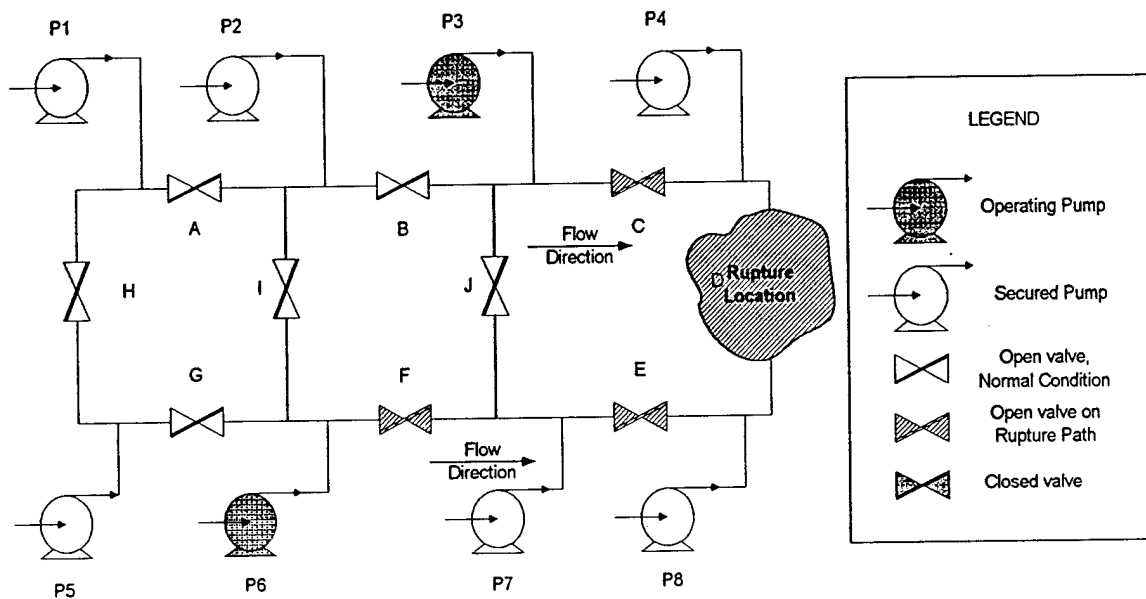


Table 7. Smart Valve Location on the Primary Rupture Path

Valve	Flow Direction ⁽¹⁾	Valve Location for Flow from Pump 3 ⁽²⁾	Valve Location for Flow from Pump 6 ⁽²⁾
C	Right	1	3
E	Right	2	2
F	Right	3	1

⁽¹⁾ The flow direction is relative to the valve based on its orientation shown in the figure above.

⁽²⁾ The valve location is the *lowest* number of the smart valves from the operating pump in the direction of flow (i.e., valves are numbered sequentially one through five in the direction of flow, with one being closest to the pump and five being furthest from the pump).

- 3) Upon determination that a smart valve is on the primary rupture flow path, a clock in the smart valve controller is started so that valve will close after a preset time delay. The preset time delay is a function of the location of the smart valve along the primary rupture flow path with respect to the operating pumps. See Table 8.

Table 8. Smart Valve Closure Time Delay for Valves on Primary Rupture Path

Location	Time to Closure (sec)
5	5
4	25
3	45
2	65
1	85

With two pumps operating, two time delays are identified and the smart valve will close based the shortest of the two time delays.

- 4) Smart valves A, B, G, H, I and J sense a low pressure but the differential pressure decreases and therefore does not trip the setpoint. Therefore these valves are not on the primary rupture path. A trigger is tripped in these valves to indicate that they are not on the primary rupture path.
- 5) Based on Tables 7 and 8, valves C and F will close at 45 seconds following the rupture. After valve C and F close, a secondary rupture flow path established. Smart valves B, I and J sense an increase in differential pressure above their setpoints indicating that they are on the secondary rupture path. The valve locations for the valves on the secondary rupture path are shown in Table 9.

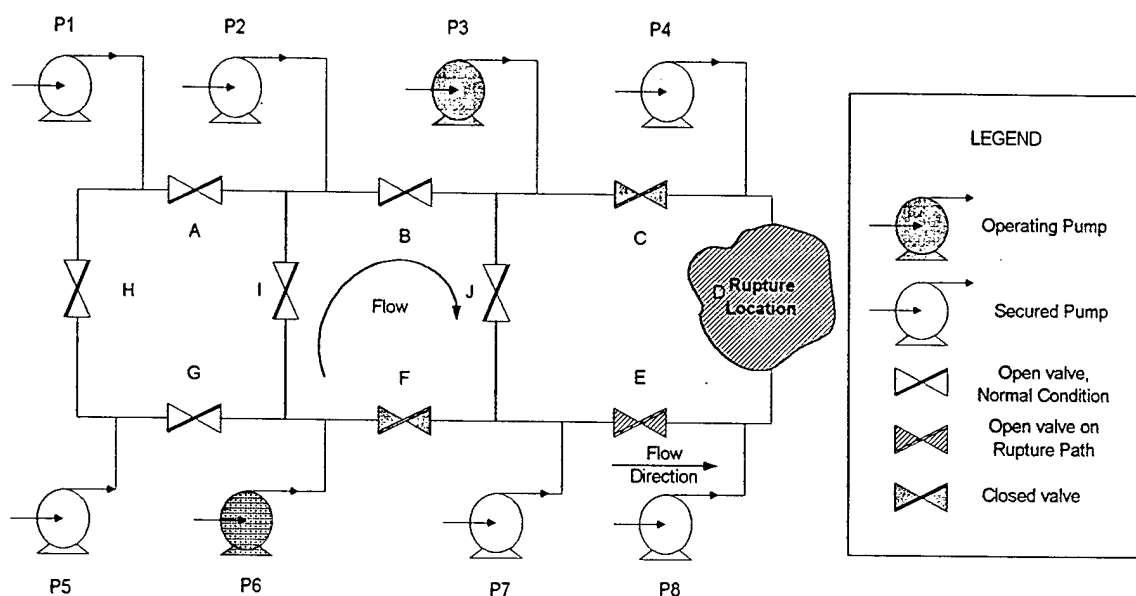


Table 9. Valve Locations for Smart Valves on the Secondary Rupture Path

Valve	Flow Direction	Valve Location for Flow from Pump 3	Valve Location for Flow from Pump 6
B	Right	4	2
I	Up	3	1
J	Down	1	3

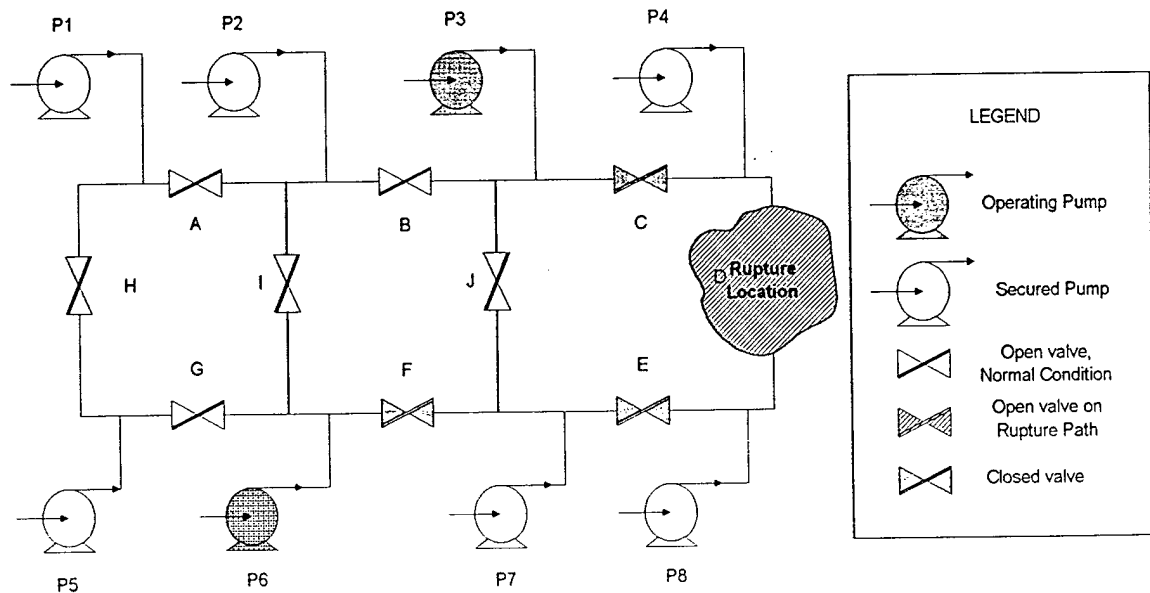
- 6) The clock is initiated for closure time delay for each of the smart valves on the secondary rupture path when their high differential pressure setpoints are exceeded in accordance with Table 10.

Table 10. Closure Time Delay for Smart Valves on Secondary Rupture Path

Location	Time to Closure (sec)
5	$5 + \delta$
4	$25 + \delta$
3	$45 + \delta$
2	$65 + \delta$
1	$85 + \delta$

The secondary time delay constant, δ , is based on rupture isolation time requirements and pump operating alignment. For this example, consider $\delta = 60$ seconds. With two pumps operating, two time delays are identified and the valve will close with the lowest time delay.

- 7) Based on primary rupture path logic in Tables 7 and 8, smart valve E will close after 65 seconds, isolating the leak and returning system pressures and flows to normal. At smart valves B, I, and J, the absolute pressure increases to normal values (above their setpoints), differential pressure decreases below their setpoints, their associated time delay clocks are reset to zero, and their operating logic is reset to normal.



- 8) Valve F senses normal pressures at its inlet and outlet. Rupture path logic indicates that damage conditions do not exist on both sides of the valve. Therefore the valve opens and its operating logic is reset to normal.

ADVANTAGES AND NEW FEATURES

The basic features of the proposed design are as follows:

- Rupture path logic can be implemented for any piping system architecture with one or more pressurized sources of fluid.
- Rupture path logic requires pressure measurements at the inlet and outlet of a valve. This can be accomplished with pressure sensors embedded in the valve body, in flanges or couplings connecting the valve to the piping, or in adjacent piping.
- No communication between piping system components is needed for the smart valve to function following damage to the piping system.
- The number of valve closure cycles is minimized. No trial and error valve cycling is needed to locate and isolate the rupture.
- For fluid systems that can be segmented by valve operations, service is restored to intact segments of the piping system.
- Ruptures are isolated even with multiple failures of components (such as valves and pumps),
- Absolute flow measurement is not required. Instead, relative increases in the pressure difference across a valve are evaluated against setpoint limits. This substantially simplifies calibration and enables satisfactory operation of the smart valve even with degraded sensors.
- Rupture path logic can be implemented with any valve design (ball, gate, butterfly or globe), actuator design, and microprocessor.
- The smart valve rupture path logic can be adapted to accommodate a variety of piping system component characteristics and system hydraulic characteristics.

ALTERNATIVES

The invention is based on the method of evaluating hydraulic data and not on the hardware specified. As a result, the invention will work with the following hardware alternatives:

- The smart valve can consist of any valve type (such as butterfly, gate, ball or globe) and any actuator type (such as electric, pneumatic or hydraulic).
- Any data communication method and protocol can be used.
- The method can be used with embedded processors located at the smart valve or central processors located at a control station.
- The pressure sensors can be embedded in the smart valve or located near the valve.
- Relative changes in flow rate can be measured using ΔP across the valve or any other flow measurement method.

CONTRIBUTIONS BY INVENTORS

Thomas Lestina: Led the research team and developed the implementation method for rupture path logic.

Dr. Fred Williams: Developed the concept for reflexive fluid systems and sponsored the research.

REFERENCE

1. NRL/MR/6180-99-8346, "Evaluation of Firemain Architectures and Supporting Reflexive Technology." March 12, 1999.